KNOWLEDGE 20
SHARING 26
CCS & CDR Summit

#4 INTEGRATING TECHNOLOGIES AND PROCESSES FOR COST EFFECTIVE CO_2 SPECIFICATIONS OVER THE CCS VALUE CHAIN

KNOWLEDGE 20
SHARING 26
CCS & CDR Summit

MODERATOR

Stijn Santen

BUSINESS DEVELOPMENT AND ADVOCACY LEADER

EBN

Stijn Santen studied chemical engineering and has worked for 18 years in Shell. He was the founder of the first successful CCU projects; Shell-Omya (1998) and Shell-OCAP (2005).

In 2019 he joined EBN to develop the CCS project Aramis. Since 2023 he is also the chairman of the CCS projects network of ZEP and organizes capacity building for governments and business development with industrial partners.

KNOWLEDGE SHARING 2026

CCS & CDR Summit

Michalis Agraniotis

SENIOR BUSINESS DEVELOPMENT MANAGER

MITSUBISHI HEAVY INDUSTRIES

Michalis Agraniotis has joined Mitsubishi Heavy Industries (MHI) in 2013. He currently works as Senior Business Development Manager on Decarbonisation Business.

He also represents MHI in the Advisory Council of Zero Emissions Platform (ZEP).

GASSNOVA

CARBON CAPTURE UTILIZATION & STORAGE AN INITIATIVE OF THE CLEAN ENERGY MINISTERIAL

zep

IEAGHG

CARBON DIOXIDE REMOVAL MISSION

MOVE THE WORLD FORW>RD MITSUBISHI HEAVY INDUSTRIES GROUP

Mitsubishi Heavy Industries

MHI’s carbon capture technology. Real world experience and lessons learnt

Workshop #4: Integrating technologies and processes for cost effective CO_2 specifications over the CCS value chain

Knowledge Sharing 2026, CCS&CDR Summit

April 15th 2026

Mitsubishi Heavy Industries, Ltd.

Mitsubishi Heavy Industries (MHI) group

Mitsubishi Heavy Industries Group Profile

1884 Foundation
140 years history

78,861 Employees
(Consolidated: As of Sep.,2025)

243 Group Companies
(Consolidated: As of Sep.,2025)

Diverse **Products**
on Land, at Sea, in the Sky, in Space

7,071.2 bil. yen
Order Received
(FY2024, Consolidated)

5,027.1 bil. yen
Revenue
(FY2024, Consolidated)

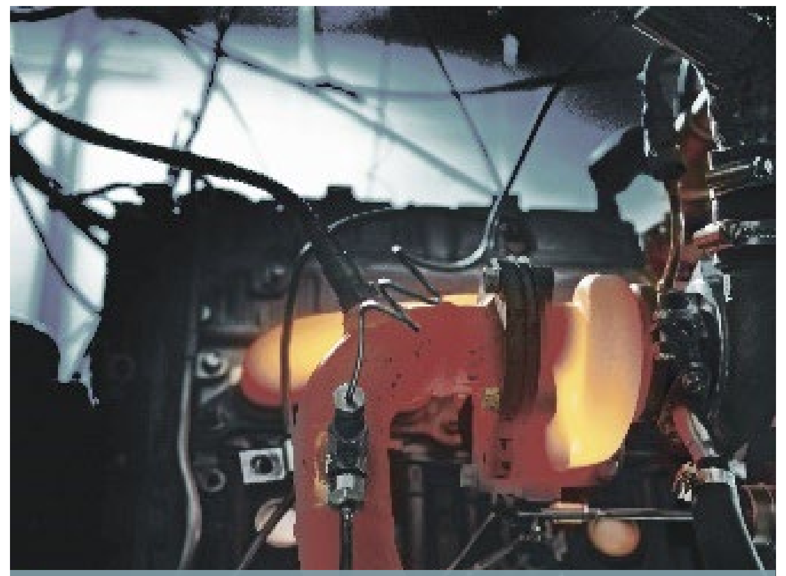
Mitsubishi Heavy Industries, Ltd. – Plants & Infrastructure Systems

Business content

- Promote energy transition business
- Engineering solutions and after-sales service for carbon capture plant, chemical plant and transportation system
- Metals Machinery business, Environmental Systems business, Commercial Ships business


H-IIA Launch Vehicle


Fighter

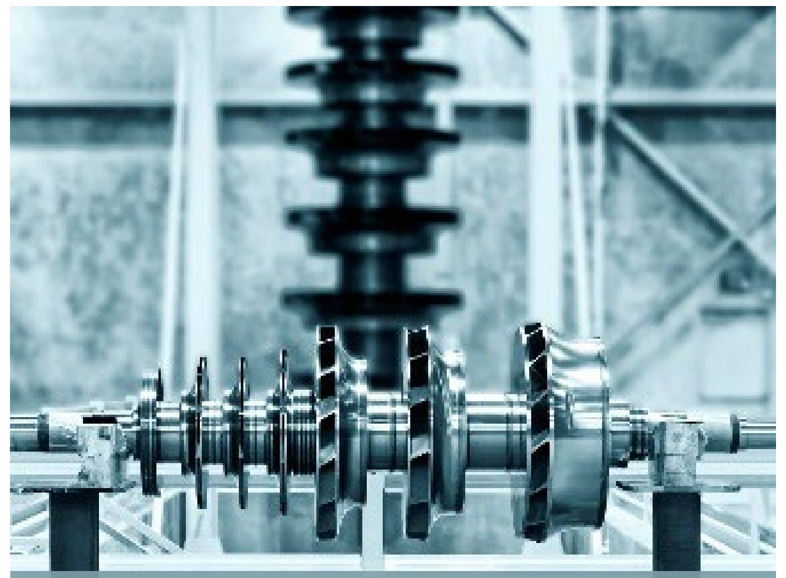

Turbocharger


Carbon Capture Plant
(Proprietary Technology)


Chemical Plant


Transportation System


Gas Turbine


Compressor


LE-7A Engine

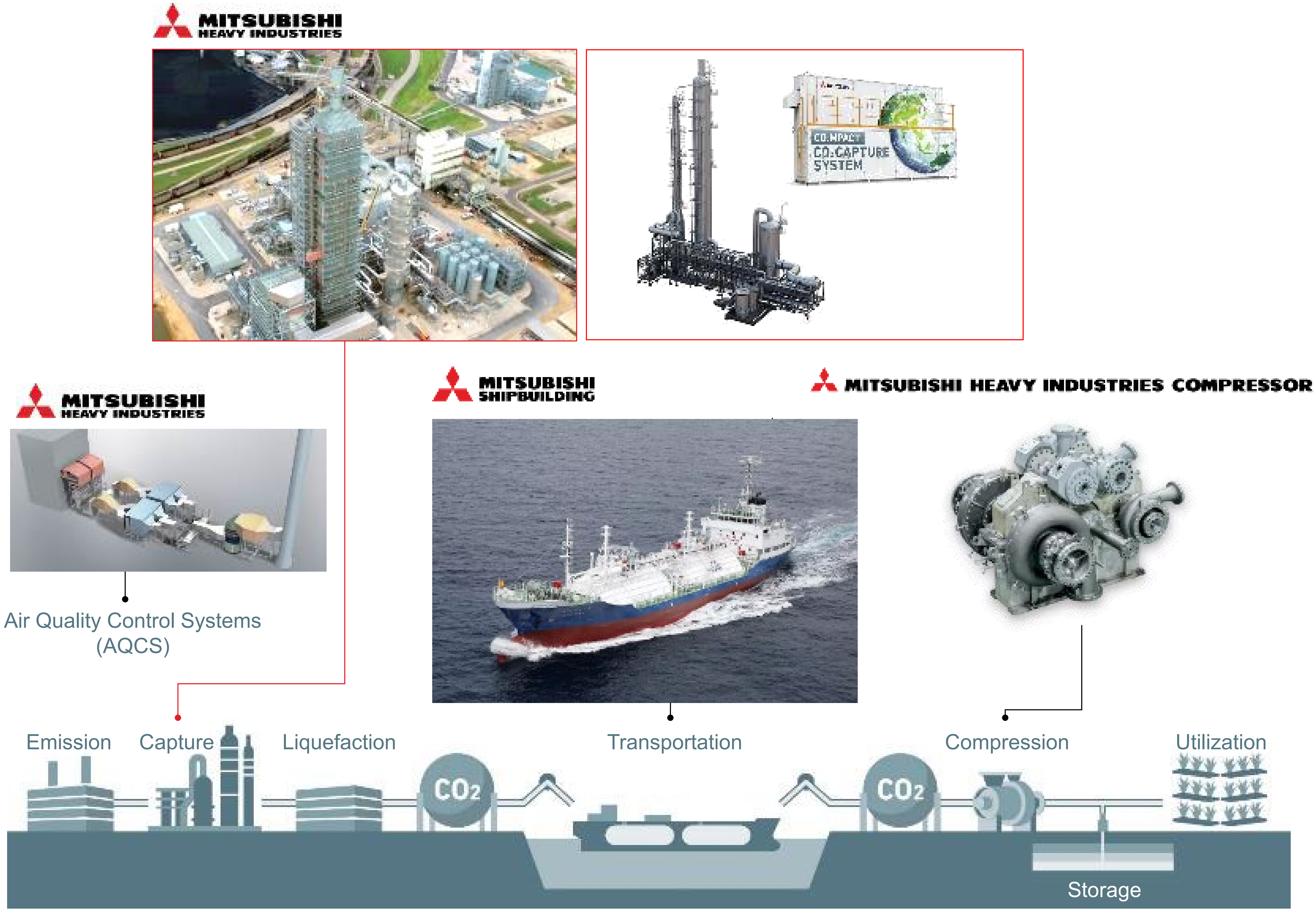

Aero Engine


Waste-to-Energy


Metal Machinery

Core technologies of the CCUS Value Chain

- MHI group has a core technologies essential for CCUS including carbon capture, transportation, storage, and compression. Carbon liquefaction is under in-house research & development (R&D) stage.
- MHI group has a solution for carbon capture and capability to collaborate with CCUS technologies.



Air Quality Control Systems (AQCS)

Emission

Capture

Liquefaction

Transportation

Compression

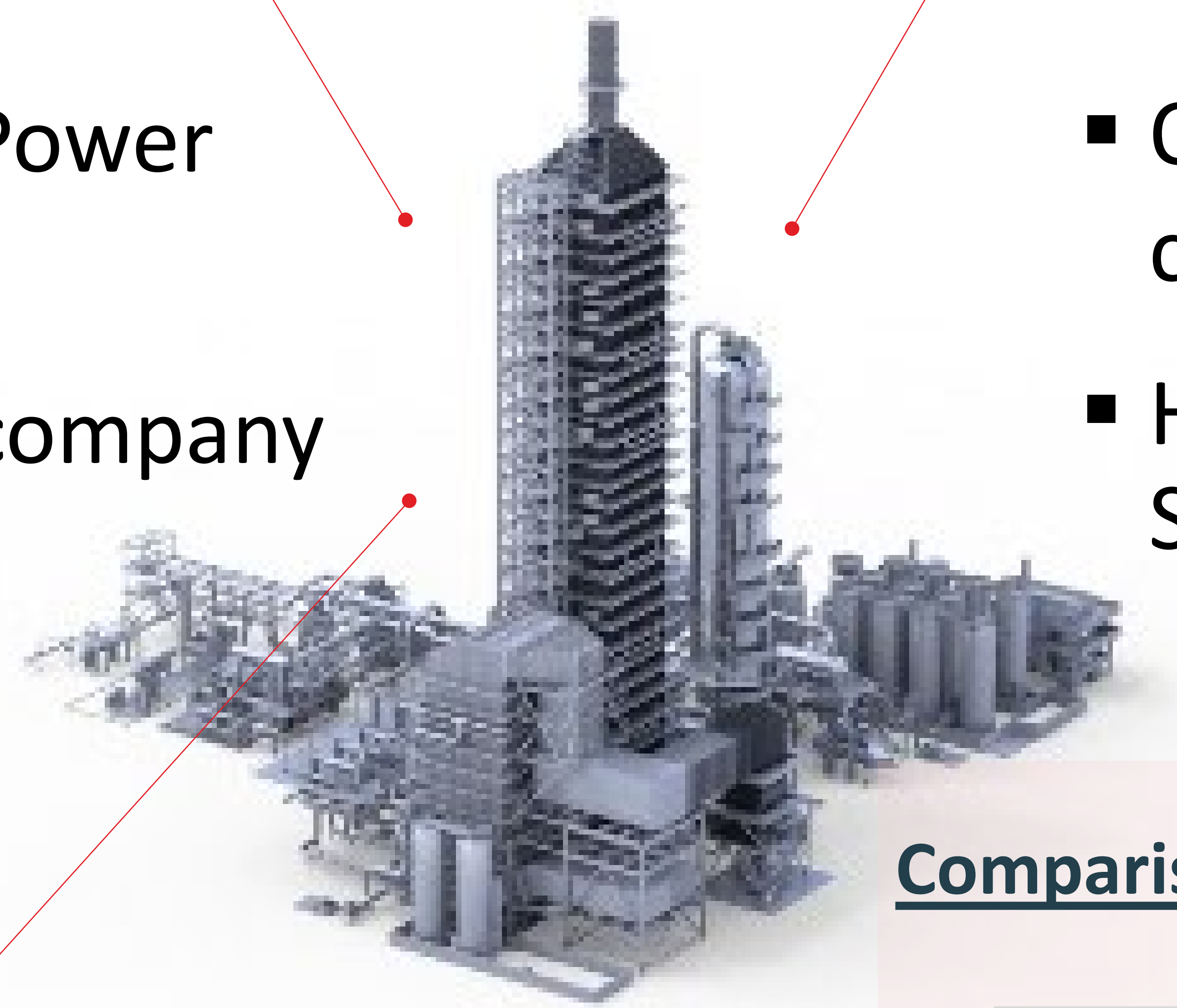
Utilization

Storage

MHI's Carbon Capture Technology

Advanced KM CDR Process ™

- **K**ansai **M**itsubishi **C**arbon **D**ioxide **R**emoval
- Jointly developed with Kansai Electric Power Company
- Kansai Electric is the 2nd largest utility company in Japan



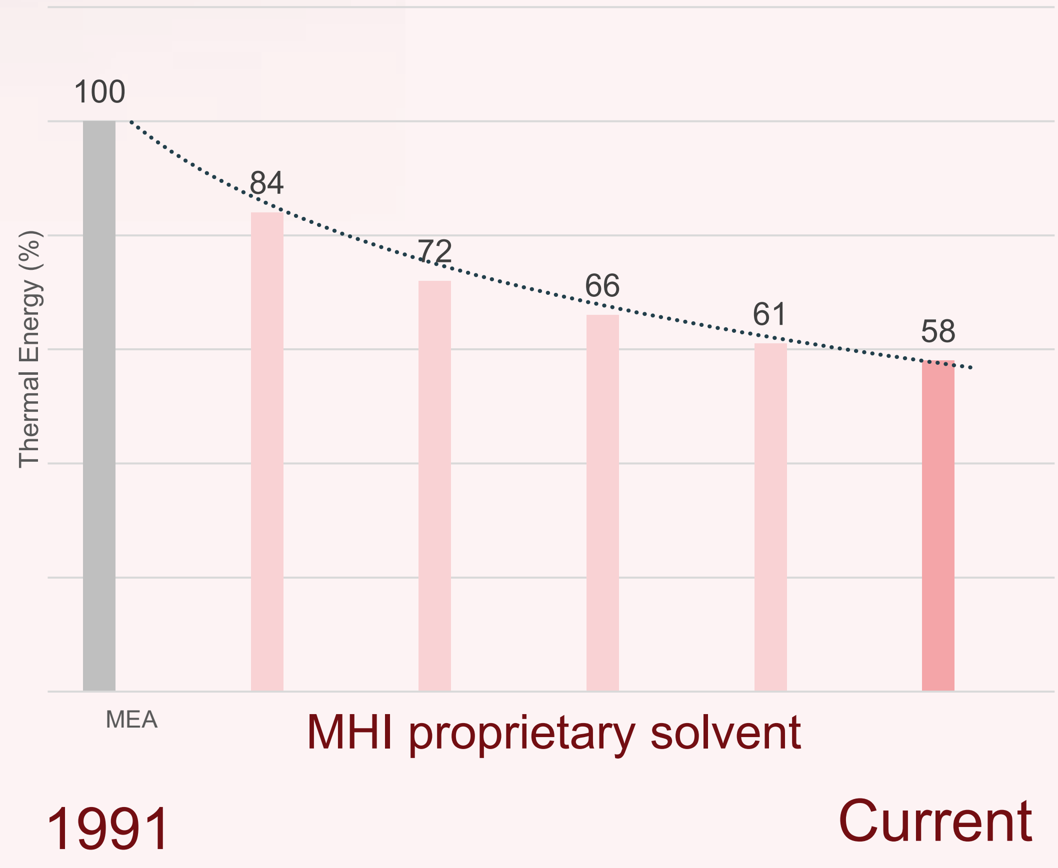
Proprietary Features

- Proprietary solvents KS-1™ / KS-21™
- Optimal utility consumptions, low corrosiveness, high stability
- High performance Heat Energy Recovery System

Technology Maturity

- R&D started 1990 – **35 years** experience
- **18 plants** for commercial operation (+2 under execution)
- **World's largest** commercial plant in service (Petra Nova)
- **Operation experience** - from CO_2 capture to compression & conditioning, pipeline delivery to CO_2 injection

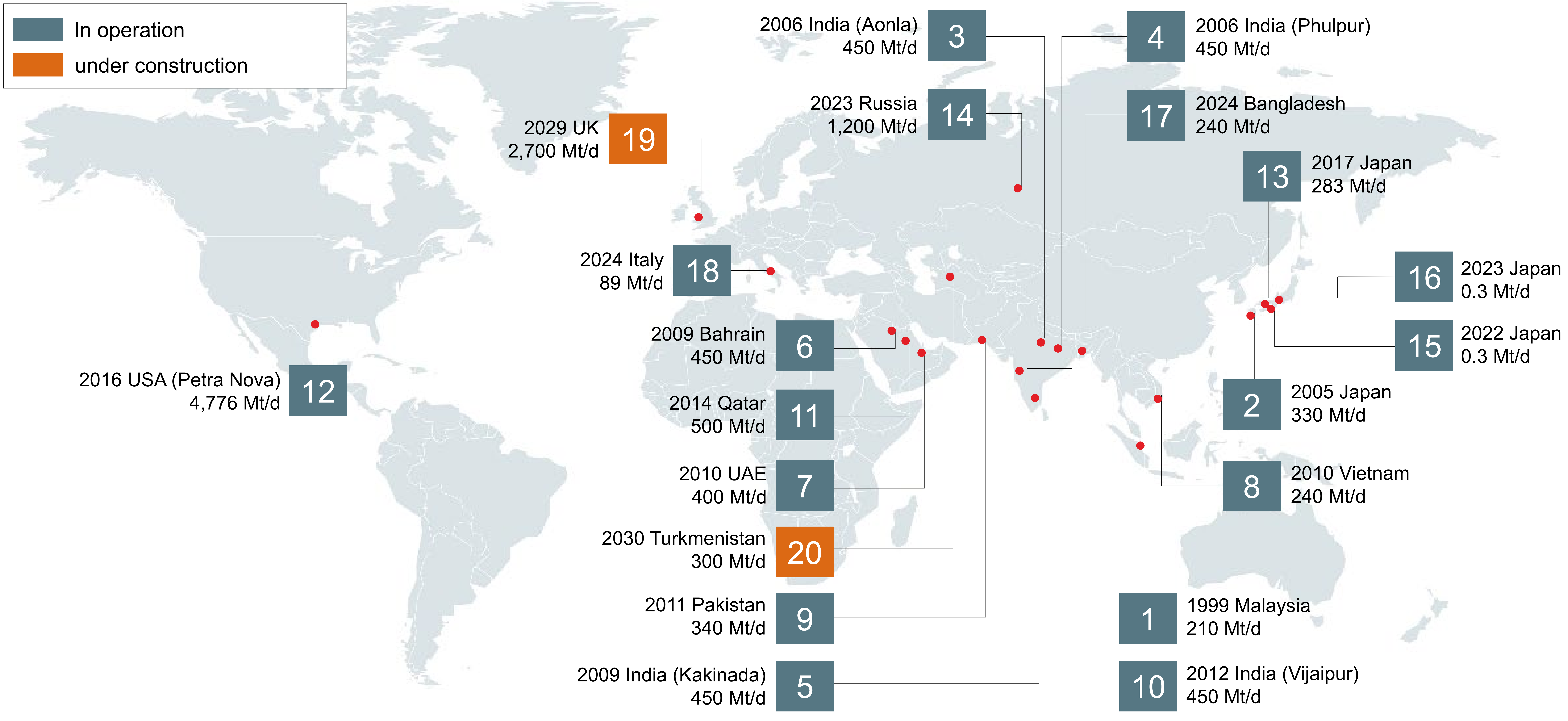
Comparison: conventional solvent (MEA) vs KS-1™ / KS-21™



- Improving since 1991
- **40%** reduction since 1991
- MHI proprietary solvent provides further efficiency

Worldwide Commercial Experience

■ In operation
🟧 under construction



1 — 1999 Malaysia 210 Mt/d
2 — 2005 Japan 330 Mt/d
3 — 2006 India (Aonla) 450 Mt/d
4 — 2006 India (Phulpur) 450 Mt/d
5 — 2009 India (Kakinada) 450 Mt/d
6 — 2009 Bahrain 450 Mt/d
7 — 2010 UAE 400 Mt/d
8 — 2010 Vietnam 240 Mt/d
9 — 2011 Pakistan 340 Mt/d
10 — 2012 India (Vijaipur) 450 Mt/d
11 — 2014 Qatar 500 Mt/d
12 — 2016 USA (Petra Nova) 4,776 Mt/d
13 — 2017 Japan 283 Mt/d
14 — 2023 Russia 1,200 Mt/d
15 — 2022 Japan 0.3 Mt/d
16 — 2023 Japan 0.3 Mt/d
17 — 2024 Bangladesh 240 Mt/d
18 — 2024 Italy 89 Mt/d
19 — 2029 UK 2,700 Mt/d
20 — 2030 Turkmenistan 300 Mt/d

Worldwide Commercial Experience

No.	Year of Delivery	Country	Flue Gas Source	CO_2 Capacity (t/d)	Application
1	1999	Malaysia	NG Fired Furnace	210	Urea Enhance Production
2	2005	Japan	NG and Heavy Oil Boiler	330	General Use
3	2006	India	NG Fired Furnace	450	Urea Enhance Production
4	2006	India	NG Fired Furnace	450	Urea Enhance Production
5	2009	India	NG Fired Furnace	450	Urea Enhance Production
6	2009	Bahrain	NG Fired Furnace	450	Urea & Methanol Enhance Production
7	2010	UAE	NG Fired Furnace	400	Urea Enhance Production
8	2010	Vietnam	NG Fired Furnace	240	Urea Enhance Production
9	2011	Pakistan	NG Fired Furnace	340	Urea Enhance Production
10	2012	India	NG Fired Furnace	450	Urea Enhance Production
11	2014	Qatar	NG Fired Furnace	500	Methanol Enhance Production
12	2016	USA	Coal-Fired Boiler	4,776	Enhanced Oil Recovery
13	2017	Japan	Gas Fired Furnace	283	General Use (Dry Ice etc.)
14	2022	Japan	Biomass Power Plant	0.3	Agriculture Use
15	2023	Russia	NG Fired Furnace	1,200	Urea & Melamine Enhance Production
16	2023	Japan	Industrial furnaces	0.3	Verification for flue gas from kiln
17	2024	Bangladesh	NG Fired Furnace	240	Urea Enhance Production
18	2024	Italy	Gas turbine for natural gas station	89	Geological Storage
19	2029	UK	Cement Plant	2,700	Geological Storage
20	2030	Turkmenistan	NG Fired Furnace	300	Urea Enhance Production

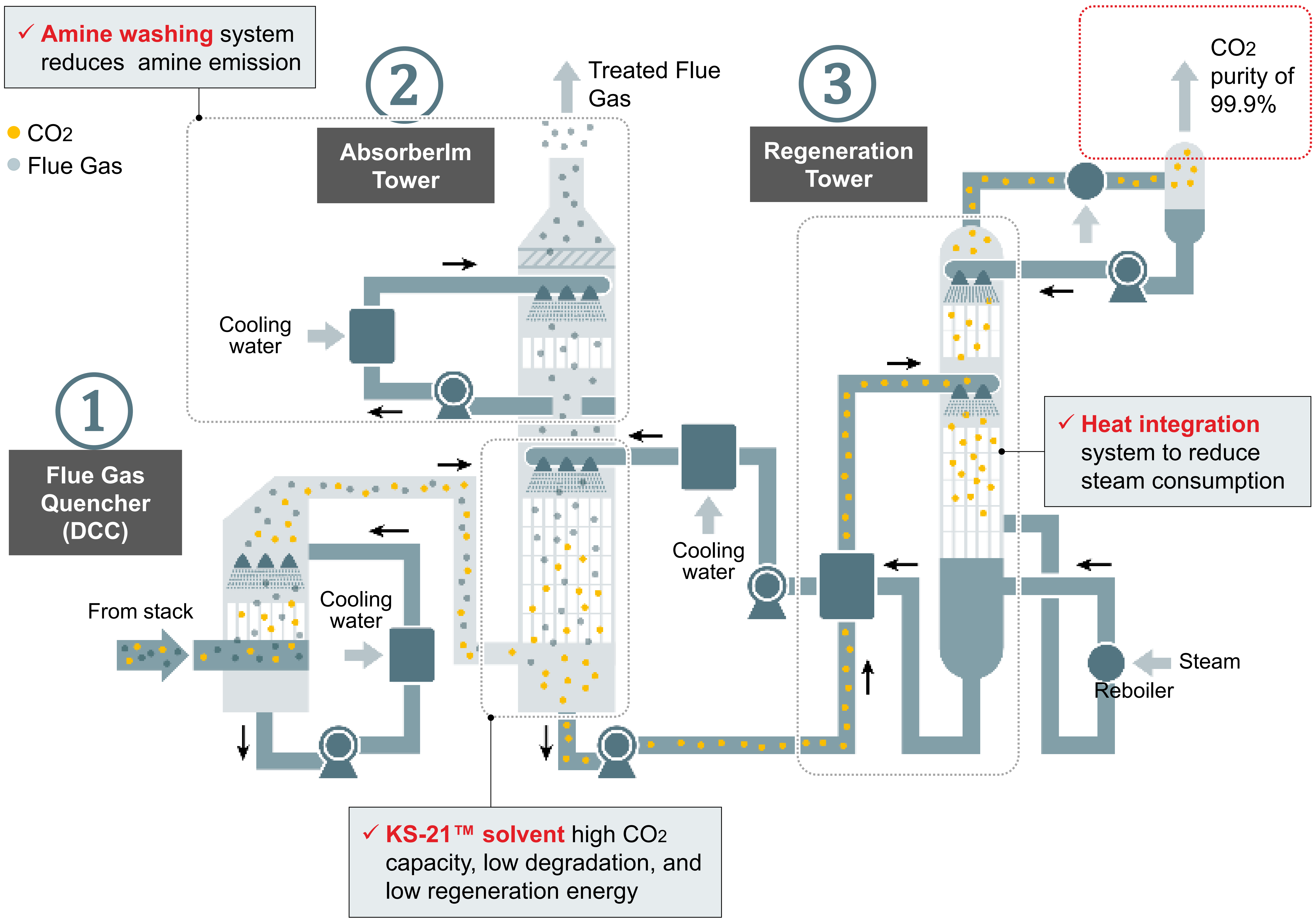
CO$_2$ impurities in post combustion capture process

CO$_2$ impurities can enter the CO2 product stream in different steps of the process:

- Impurities from flue gas carried over to the amine loop (e.g. SOx, NOx) and then to the CO$_2$ product through the regeneration process
- Impurities from amine degradation *(can be minimized through proper solvent, selection & management - reclaiming)*
- Impurities from other CO$_2$ processing steps (CO2 compression, dehydration)

Governing mechanisms:

- Physical equilibrium (Henry's law)
- Liquid droplets entrainment
- Chemical degradation, decomposition



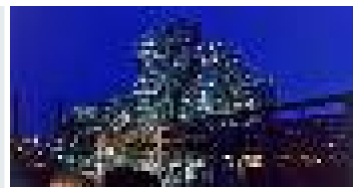
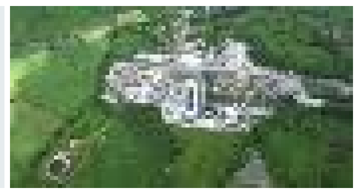
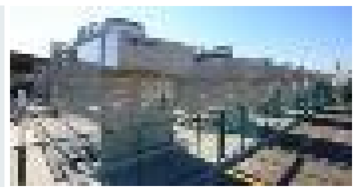
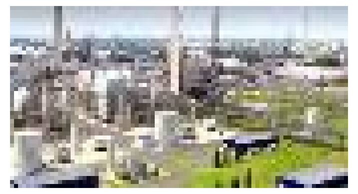
✓ **Amine washing** system reduces amine emission

✓ **Heat integration** system to reduce steam consumption

✓ **KS-21™ solvent** high CO2 capacity, low degradation, and low regeneration energy

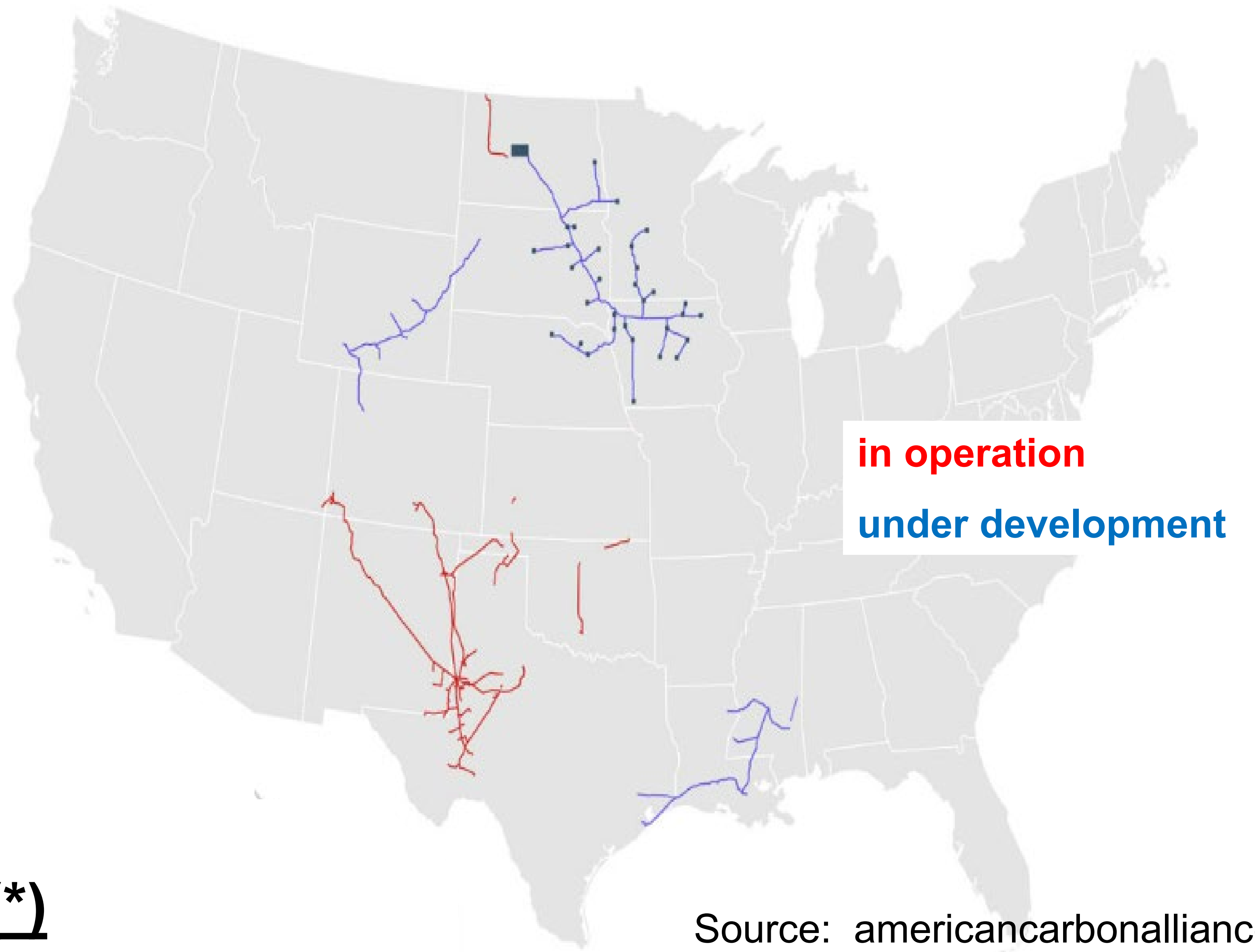
Applicability to various carbon emission sources

- MHI is expanding the number of applications for carbon capture based on core technology.
- MHI is using standardized mobile test units to evaluate effect of different flue gas types on process and emissions

Power generation	**World's largest carbon capture plant (as of 2023)**	Petra Nova	
Biomass	**License granted for first BECCS project of its kind in Europe**	Drax	
LNG liquefaction	**Feasibility Study/PDP for low-carbon production of LNG production**	NextDecade	
Refinery	**Basic design package for the UK's first low-carbon refinery**	Essar Oil UK	
Cement	**Feasibility Study/ FEED awarded at the UK and Canada**	Heidelberg Materials	
Steel	**Technology verification on multiple emission sources in ironmaking process in Belgium and North America**	ArcelorMittal, S.A.	
Shipping	**Onboard carbon capture system verified in field (on an actual voyage)**	"K" Line	
Waste-to-Energy	**Technology verification on emission from WtE process**	Yokohama-city, Japan	
Gas Engines	**Technology verification on CO2 capturing from internal Gas Engines and liquefaction**	Mitsubishi Heavy Industries Engine & Turbocharger Pilot Plant	
Ceramic	**World's first application in the ceramic manufacturing process**	NGK	
Hydrogen	**CO2 capture at the UK's largest blue H2 plant**	EET Hydrogen	

CO_2 pipeline infrastructure in US

- 8500 km operating CO_2 pipelines (50 active pipeline systems) in US with capacity of appr. 70 MTPA
- Denbury operates approx. 2090 km, Kinder Morgan operates approx. 2400 km of pipelines
- Most of the existing pipelines built for EOR, not sequestration
- CO_2 pipeline network in US keeps expanding. Future growth depending not on technology, but on public acceptance and permitting processes



Source: americancarbonalliance

Kinder Morgan

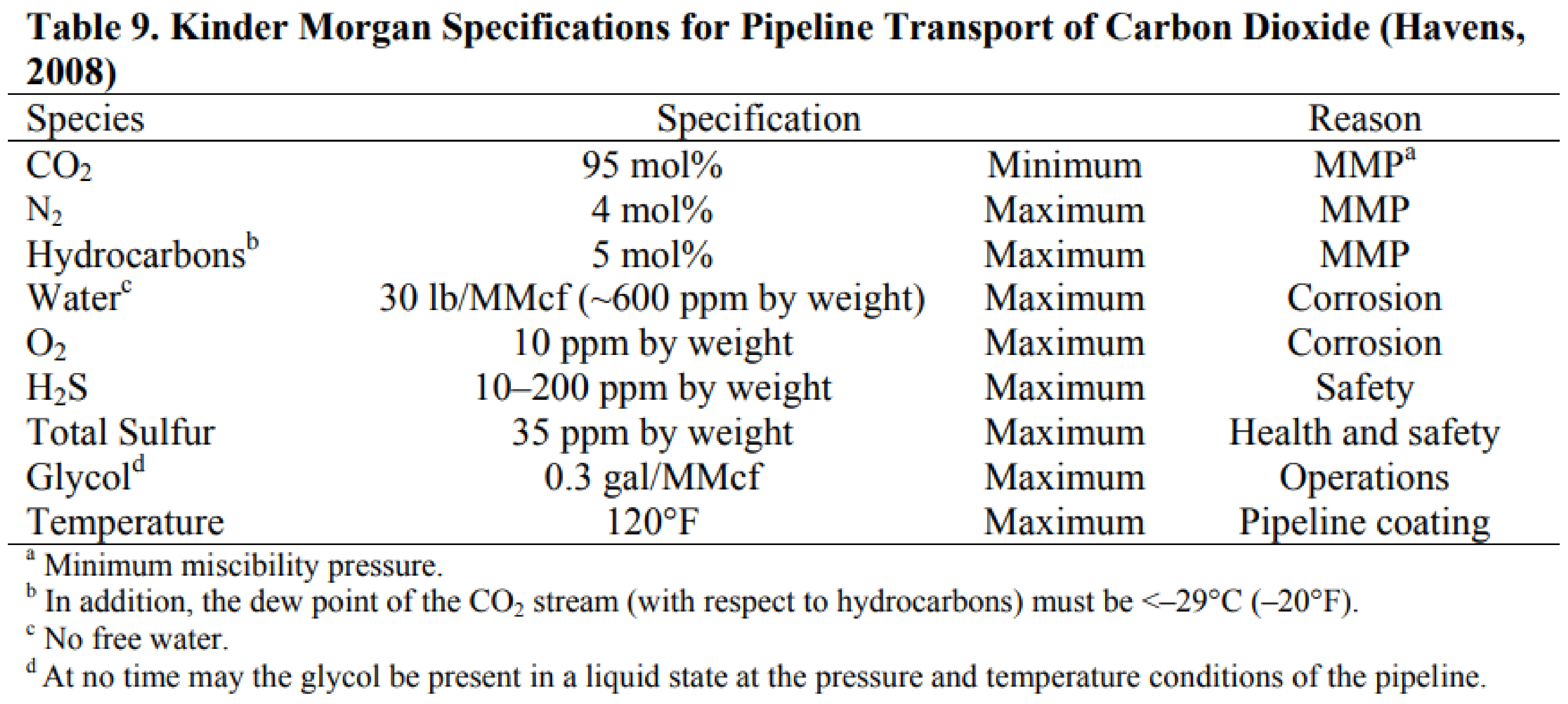


Table 9. Kinder Morgan Specifications for Pipeline Transport of Carbon Dioxide (Havens, 2008)

Species	Specification		Reason
CO_2	95 mol%	Minimum	MMP[a]
N_2	4 mol%	Maximum	MMP
Hydrocarbons[b]	5 mol%	Maximum	MMP
Water[c]	30 lb/MMcf (~600 ppm by weight)	Maximum	Corrosion
O_2	10 ppm by weight	Maximum	Corrosion
H_2S	10–200 ppm by weight	Maximum	Safety
Total Sulfur	35 ppm by weight	Maximum	Health and safety
Glycol[d]	0.3 gal/MMcf	Maximum	Operations
Temperature	120°F	Maximum	Pipeline coating

[a] Minimum miscibility pressure.

[b] In addition, the dew point of the CO_2 stream (with respect to hydrocarbons) must be <–29°C (–20°F).

[c] No free water.

[d] At no time may the glycol be present in a liquid state at the pressure and temperature conditions of the pipeline.

https://www.osti.gov/servlets/purl/1176874

Denbury (Exxon Mobil) (*)

Species	unit	Specication
CO_2	Vol.	≥ 97
water	“	≤ 210
O_2	“	≤ 10
H_2S	ppm	≤ 10
S	“	≤ 10
SOx	“	≤ 10
NOx	“	≤ 10

(*) Excerpt from list https://www.rrc.texas.gov/media/0d5pi4z5/1-0-0.pdf

MHI’s project experience in US

Petra Nova Project

The World’s Largest Post-Combustion Carbon Capture Plant

EPC full turnkey project

- MHI has provided the world’s largest carbon capture plant on coal-fired flue gas delivered in December 2016
- Supported by DOE (U.S. Department of Energy) grant program (CCPI* Round 3) and Japanese government finance (JBIC / NEXI)

Project Formation	•Consortium of MHI / The Industrial Company (TIC) (MHI: Engineering and Procurement for Carbon Capture Plant)
Plant location	NRG WA Parish Power Plant (Thompsons, TX)
Project owner	Petra Nova - full ownership under ENEOS Xplora Inc.
Plant scale	240 MW_{eq}
CO_2 capacity	4,776 t/d (1.4 Mt/y)

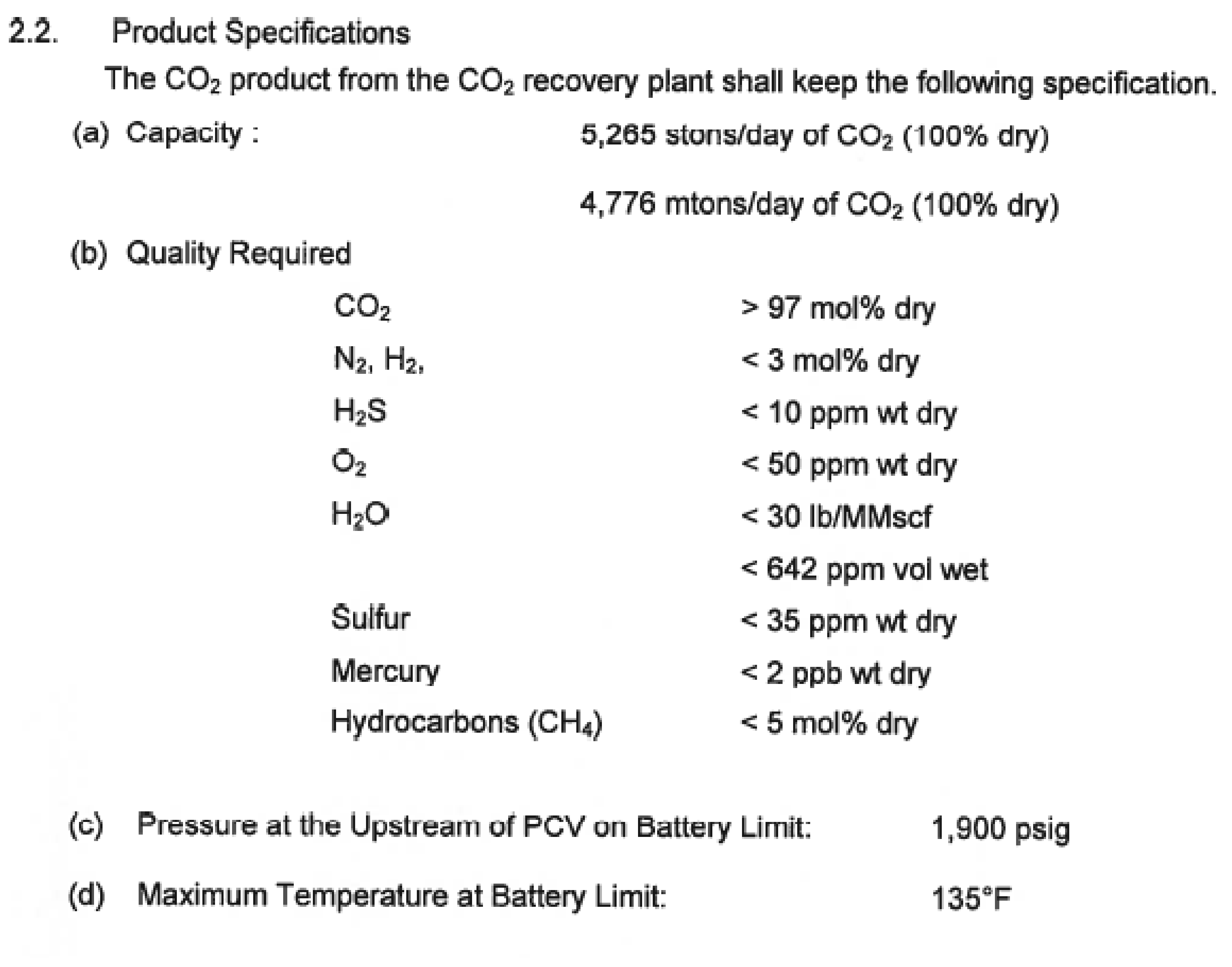
Carbon Capture Plant

*Clean Coal Power Initiative

*U.S. Department of Energy “W.A. Parish Post-Combustion CO_2 Capture and Sequestration Project Final Environmental Impact Statement Volume I” (Feb, 2013), DOE/EIS-0473

Source: Press Release by MHI

Petra Nova – design conditions



2.2. Product Specifications

The CO_2 product from the CO_2 recovery plant shall keep the following specification.

(a) Capacity : 5,265 stons/day of CO_2 (100% dry)

4,776 mtons/day of CO_2 (100% dry)

(b) Quality Required

CO_2	> 97 mol% dry
N_2, H_2,	< 3 mol% dry
H_2S	< 10 ppm wt dry
O_2	< 50 ppm wt dry
H_2O	< 30 lb/MMscf
	< 642 ppm vol wet
Sulfur	< 35 ppm wt dry
Mercury	< 2 ppb wt dry
Hydrocarbons (CH_4)	< 5 mol% dry

(c) Pressure at the Upstream of PCV on Battery Limit: 1,900 psig

(d) Maximum Temperature at Battery Limit: 135°F

Source: https://www.cfaenm.org/wp-content/uploads/2019/03/DOE-report-on-250-MW-CCS-project.pdf

CO_2 conditioning system

- 8 stage internal gear compressor (MHI) up to supercritical condition
- TEG dehydration unit

→ In operation since 2016 (stop during COVID)

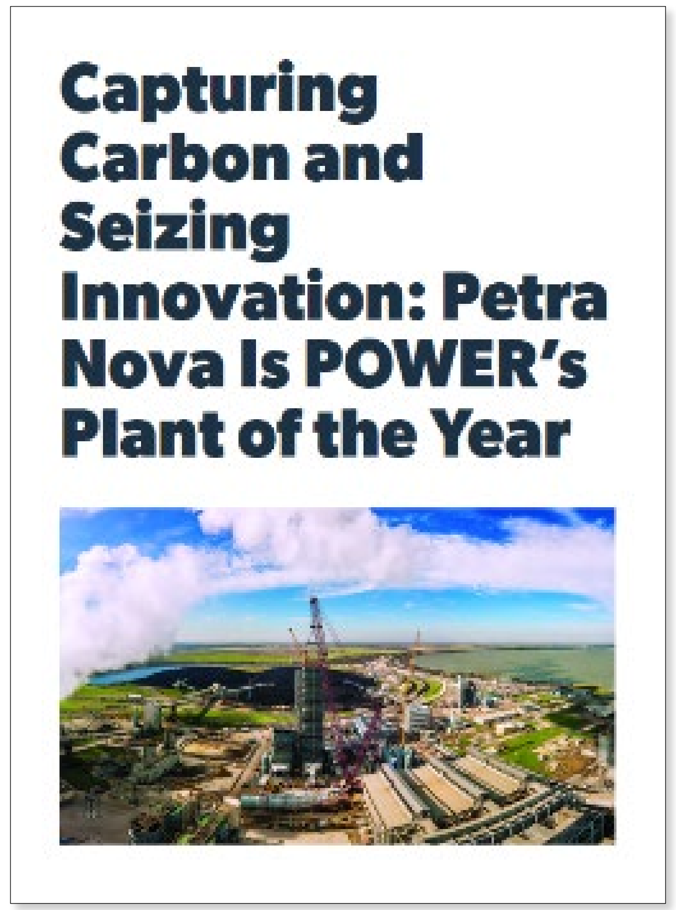
Petra Nova Project

"On-Budget and On-Schedule"

NRG Energy, JX Nippon Complete World's Largest Post-Combustion Carbon Capture Facility On-Budget and On-Schedule

Power Magazine

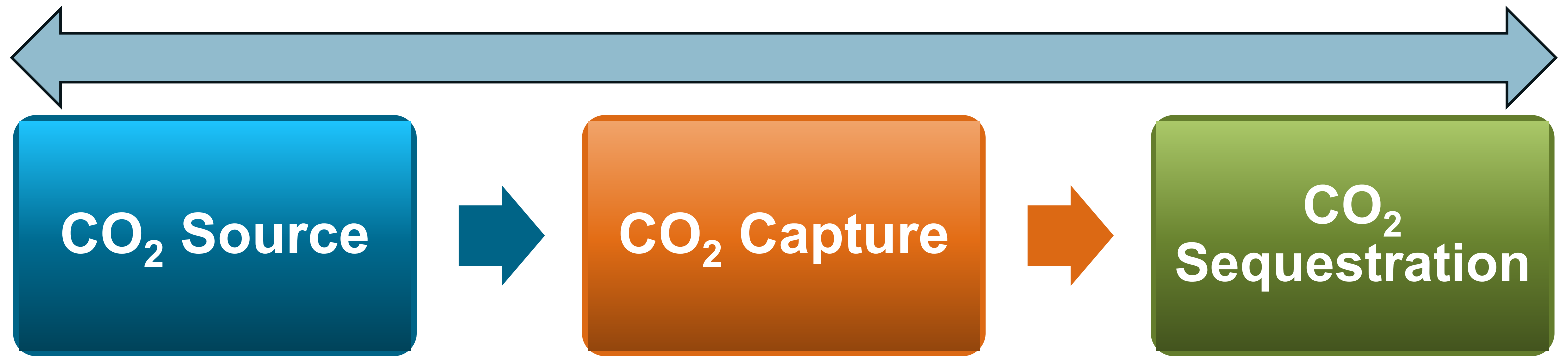
"Plant of the Year" August 2017



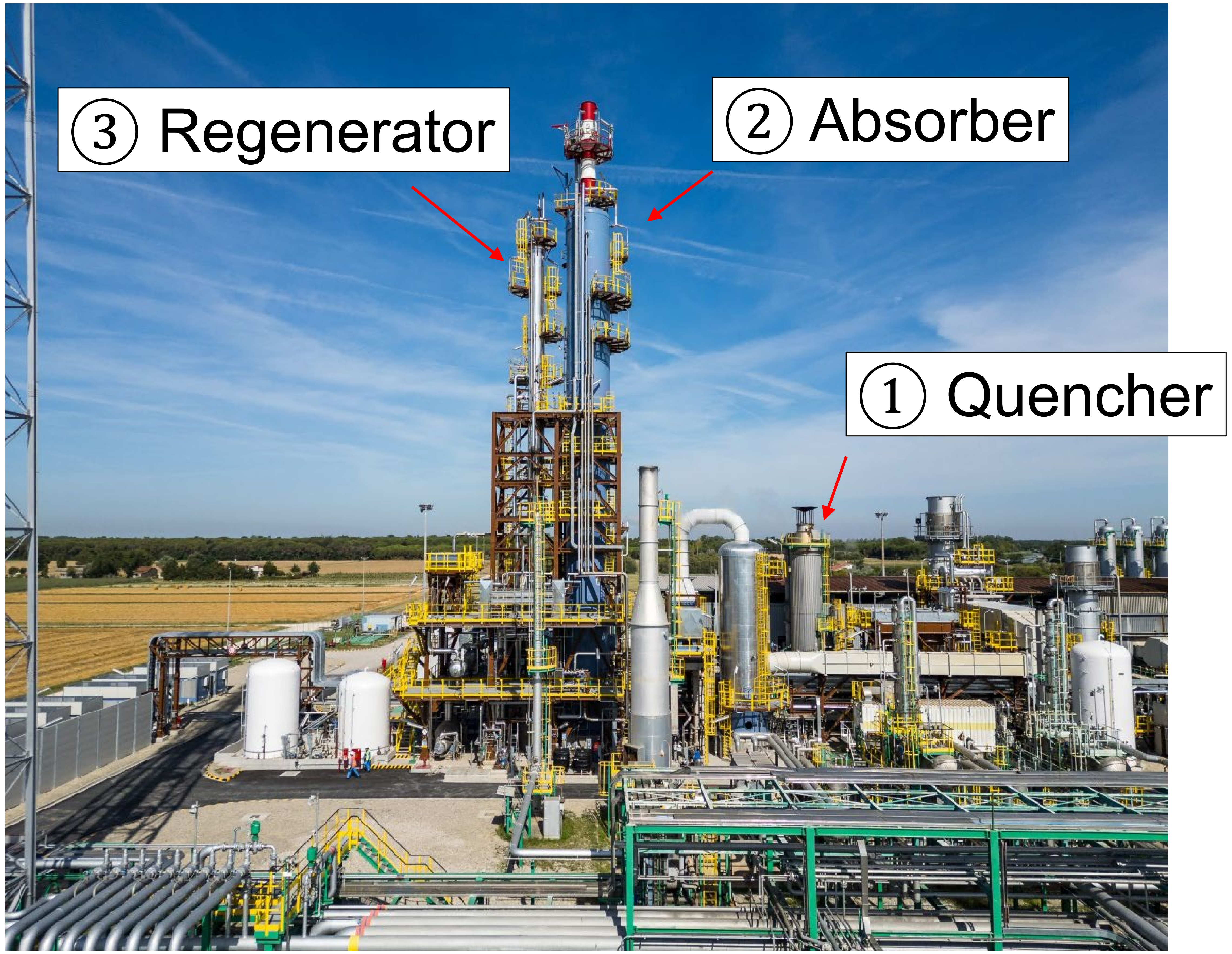
Capturing Carbon and Seizing Innovation: Petra Nova Is POWER's Plant of the Year

Ravenna CCS Hub – Casalborseti plant

Europe's First Post-Combustion Carbon Capture Plant with Storage starts Operation at ENI, Italy with MHI Technology as part of the Ravenna CCS Project, Phase 1

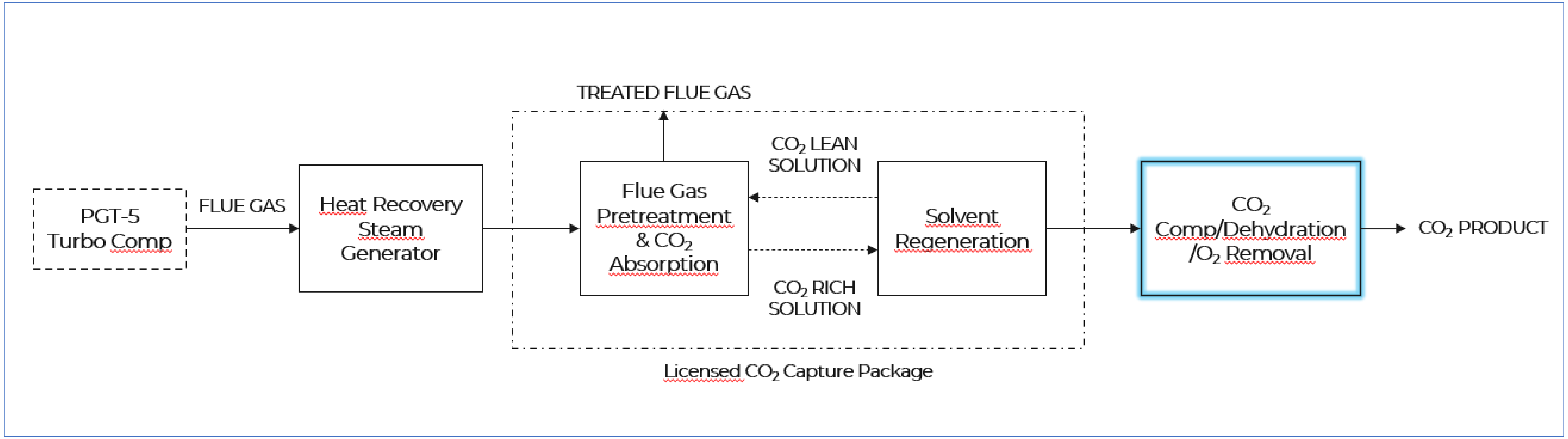


Project Formation	▪ Carbon Capture plant is installed at ENI's Casalborseti natural gas plant near Ravenna, Italy ▪ MHI is working in partnership with NEXTCHEM, MAIRE's subsidiary dedicated to the energy transition,
Key Feature	• Plant captures CO_2 from flue gas with the lowest concentration < 3%vol. • > 95% capture rate. • First complete end to end solution from capture to storage in Europe.
CO2 Source of Emissions	• Gas Turbine
CO2 capacity	89 t/d (25,000 tpa)



Carbon capture plant for Ravenna CCS (photo courtesy of Eni S.P.A)

Capture process at Casalborsetti plant



- The key process steps include:
- Flue Gas Cooling: Exhaust gas (~500°C) is directed into a Heat Recovery Steam Generator, reducing temperature to ~200°C;
- Quenching & Absorption: The gas is further cooled in a quenching column (~35°C), then fed to the absorber where CO_2 is removed using an amine solvent;
- Regeneration: The solvent is regenerated in a stripper column, releasing high purity CO_2;
- Compression: CO_2 is compressed in a four-stage unit (30 or 50 bar);
- CO_2 Conditioning

courtesy of Ravenna CCS Project

CO_2 Conditioning

To guarantee the required purity for transport, after the onshore compression CO_2 stage undergoes:

- Oxygen removal (H_2 reaction)
- Dehydration (molecular sieves)

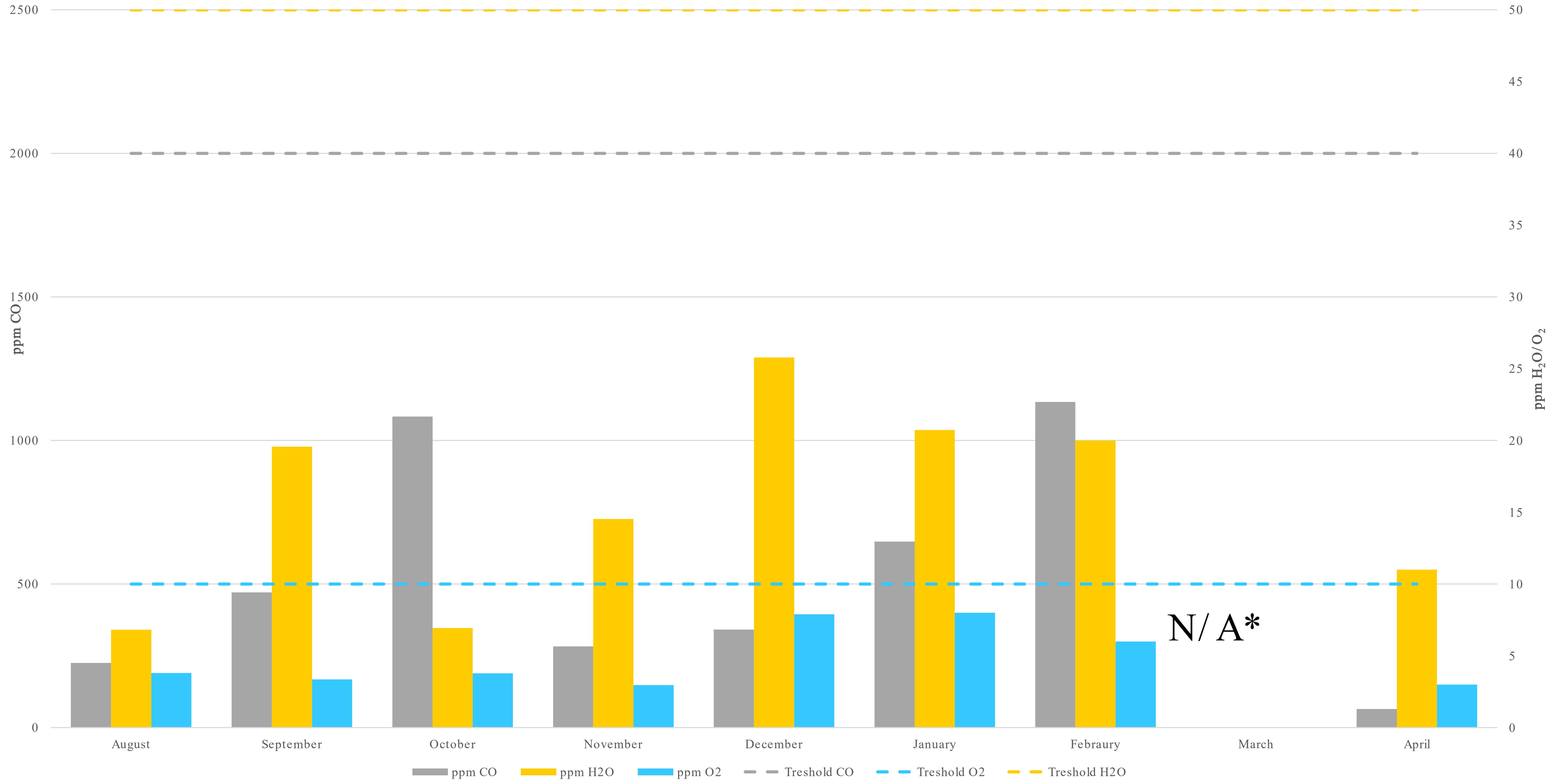
Continuous monitoring showed that:

- Average CO_2 **purity is >99.5%**
- O_2, CO and H_2O content is well below specified limits

Additionally, time-matched periodic gas samples were collected and analyzed at the pipeline inlet and at the wellhead:

- H_2S, NOx, SOx are below detectability threshold (2-3ppm)
- Matching H_2O content shows that there is no evidence of acid drop-out

Purification package



* Casalborsetti compressor planned maintenance during March

courtesy of Ravenna CCS Project

Conclusions

- CO_2 transport in pipelines and vessels has been an industrial practice for some decades. Considerable experience in US and Canada
- Need to utilise experience in design and operation from CO_2 projects worldwide
- What is new in European development? a) mixing of CO_2 from various flue gas sources , b) multimodal transport, c) CCS & CCU
- Comprehensive design process across the CO_2 value chain

→ identify risks and mitigation options at the most suitable part of the value chain towards total optimised solution.

Contacts & Information

- For any inquiry about MHI Carbon capture technology, please feel free to contact:

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Or, you may meet us on the web:
visit us at > https://www.mhi.com/business/engineering

our Carbon capture technology
on > https://www.youtube.com/watch?v=9PtnuRWOQAY

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Manuel Herraiz

DIRECTOR, BUSINESS DEVELOPMENT

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Manuel Herraiz is the Director of Business Development at Siemens Energy, where he focuses on decarbonisation solutions with a particular emphasis on carbon capture. Based in Houston, he leads global CCUS business development efforts and drives strategic partnerships to accelerate innovations and deployment of low-carbon technologies.

GASSNOVA

CARBON CAPTURE UTILIZATION & STORAGE AN INITIATIVE OF THE CLEAN ENERGY MINISTERIAL zep IEAGHG MI CARBON DIOXIDE REMOVAL MISSION

Workstream #4

Integrating Technologies and Processes for Cost Effective CO_2 Specifications over the CCS Value Chain

Siemens Energy

Sandefjord, 15 April 2026

In this market environment,

Siemens Energy is a global leader in energy technology

~1/6
of global electricity generation is based on our technology

103,000
employees work as a team to energize society[1]

>90
We are present in more than 90 countries

€39.1 bn
in revenue[2]

[1] Number of employees as of September 30, 2025
[2] Revenue FY 2025

And we have a strong team driving it

Guiding #TeamPurple in times of uncertainty

Executive Board

Christian Bruch

CEO

Maria Ferraro

CFO

Karim Amin

Gas Services

Tim Holt

Grid Technologies

Anne-Laure de Chammard

Transformation of Industry

Vinod Philip

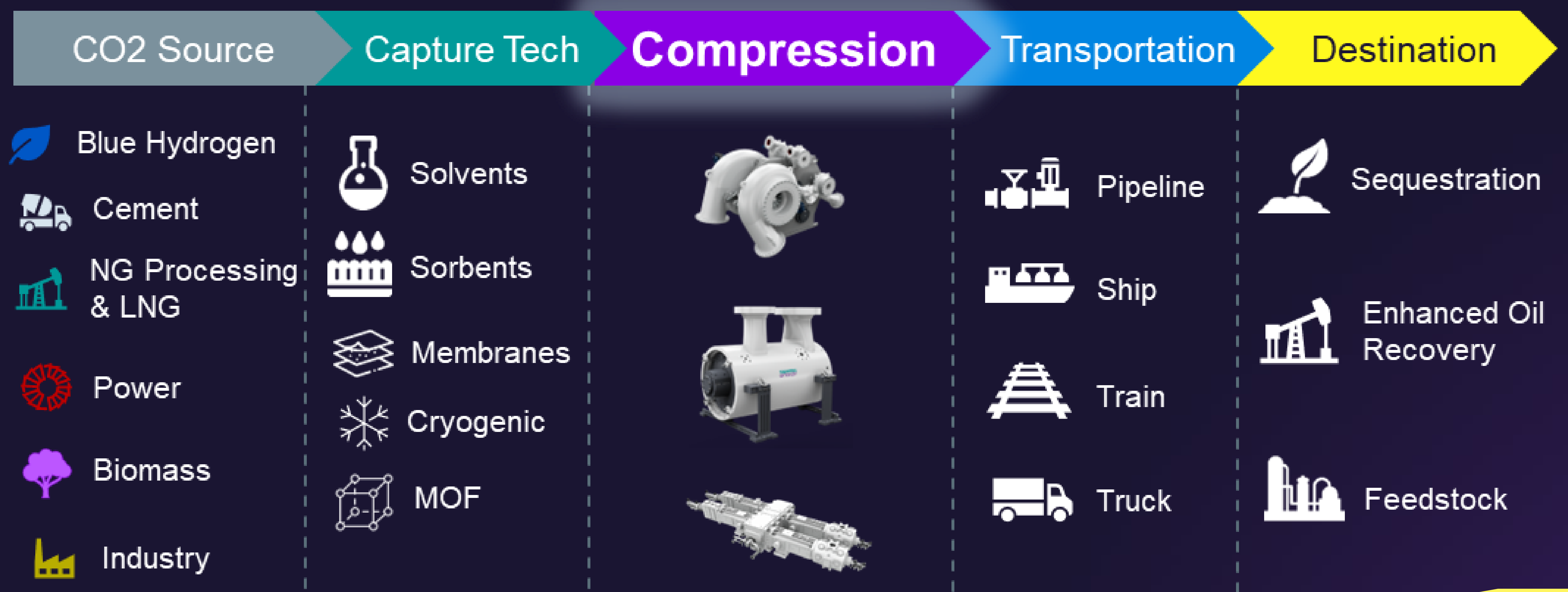
Siemens Gamesa

Reporting Segments

CO_2 Compression Experience and Opportunities

Carbon Forwarding

Managing Constituents & Energy



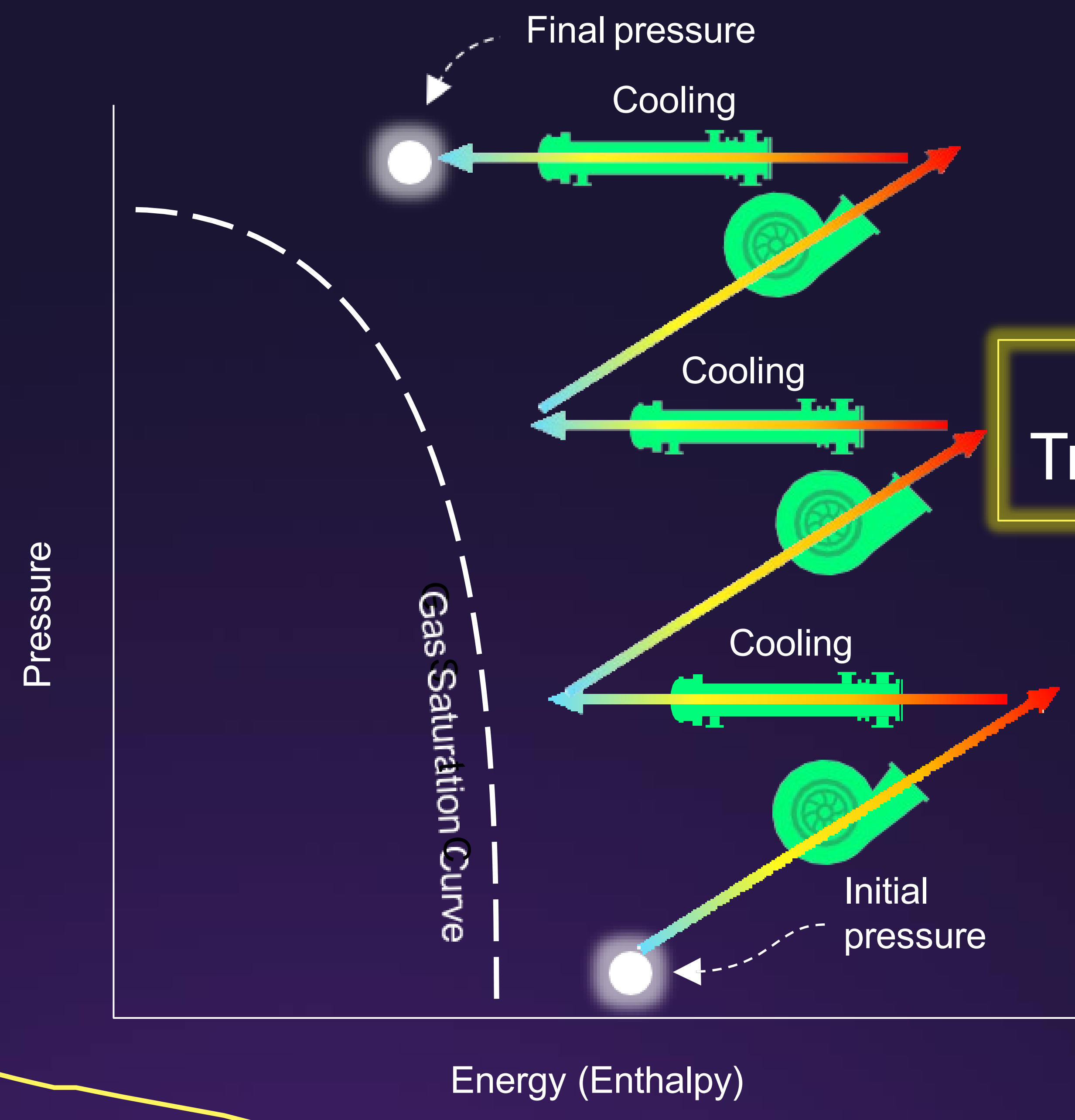
CO2 Source
- Blue Hydrogen
- Cement
- NG Processing & LNG
- Power
- Biomass
- Industry

Capture Tech
- Solvents
- Sorbents
- Membranes
- Cryogenic
- MOF

Compression

Transportation
- Pipeline
- Ship
- Train
- Truck

Destination
- Sequestration
- Enhanced Oil Recovery
- Feedstock



Gas Treatment

Typical Contaminants		0 bar	20 bar	>150 bar
	NO_x	Removed pre-capture	10 ppmv	10 ppmv
	SO_x	Removed pre-capture	10 ppmv	10 ppmv
	H_2O	2-5% mol	10 ppmv	50 – 650 ppmv
	O_2	<1% mol	10 ppmv	10 ppmv
	N_2	<5% mol	-	<3%

Energy Efficiency Impact

Equipment Specification

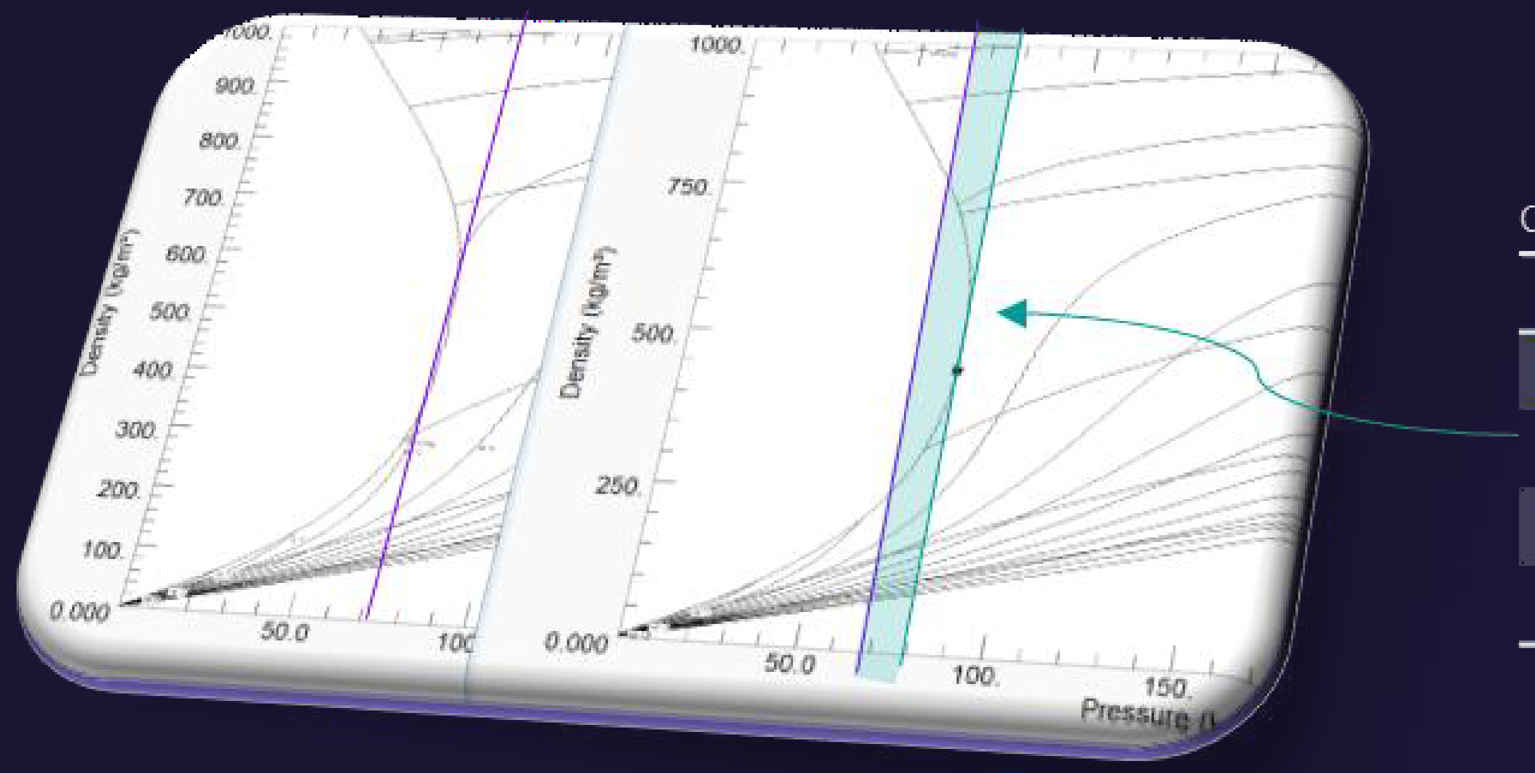
Domino Effect

The Paradigm Shift from “Purity” to “Sweet Spot”

Energy Efficiency Impact

Phase transitions shift to higher pressure with CO_2 mixtures

The Power Penalty: A CO_2 stream with just 4-5% non-condensables can increase the specific compression power requirement by 7-10%.



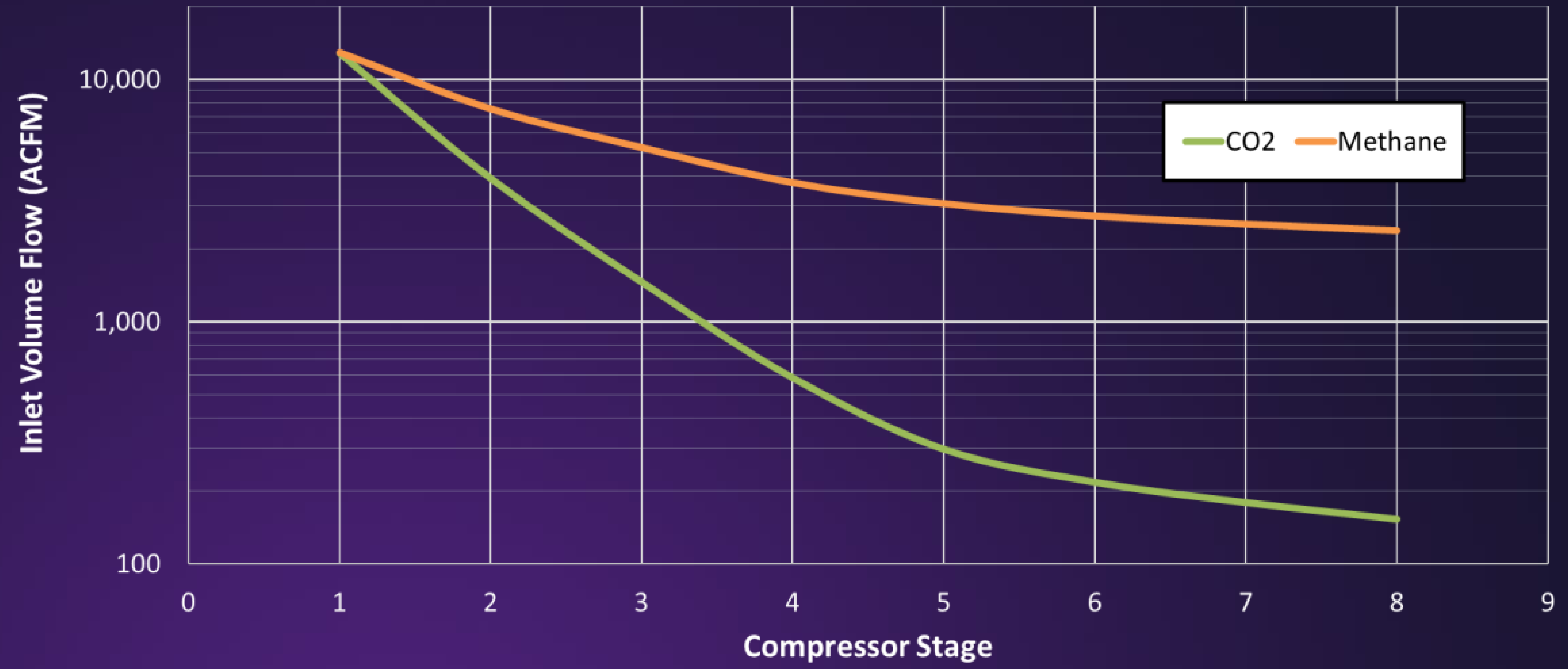
CO2 Mixture

Component	Mol%
CO2	97
N2	2
O2	0.5
CH4	0.5

Domino Effect

Value chain inefficiencies

Non-condensable impurities reduce the density of the CO_2 plume. A5% impurity level can reduce the effective storage capacity by up to 30%.

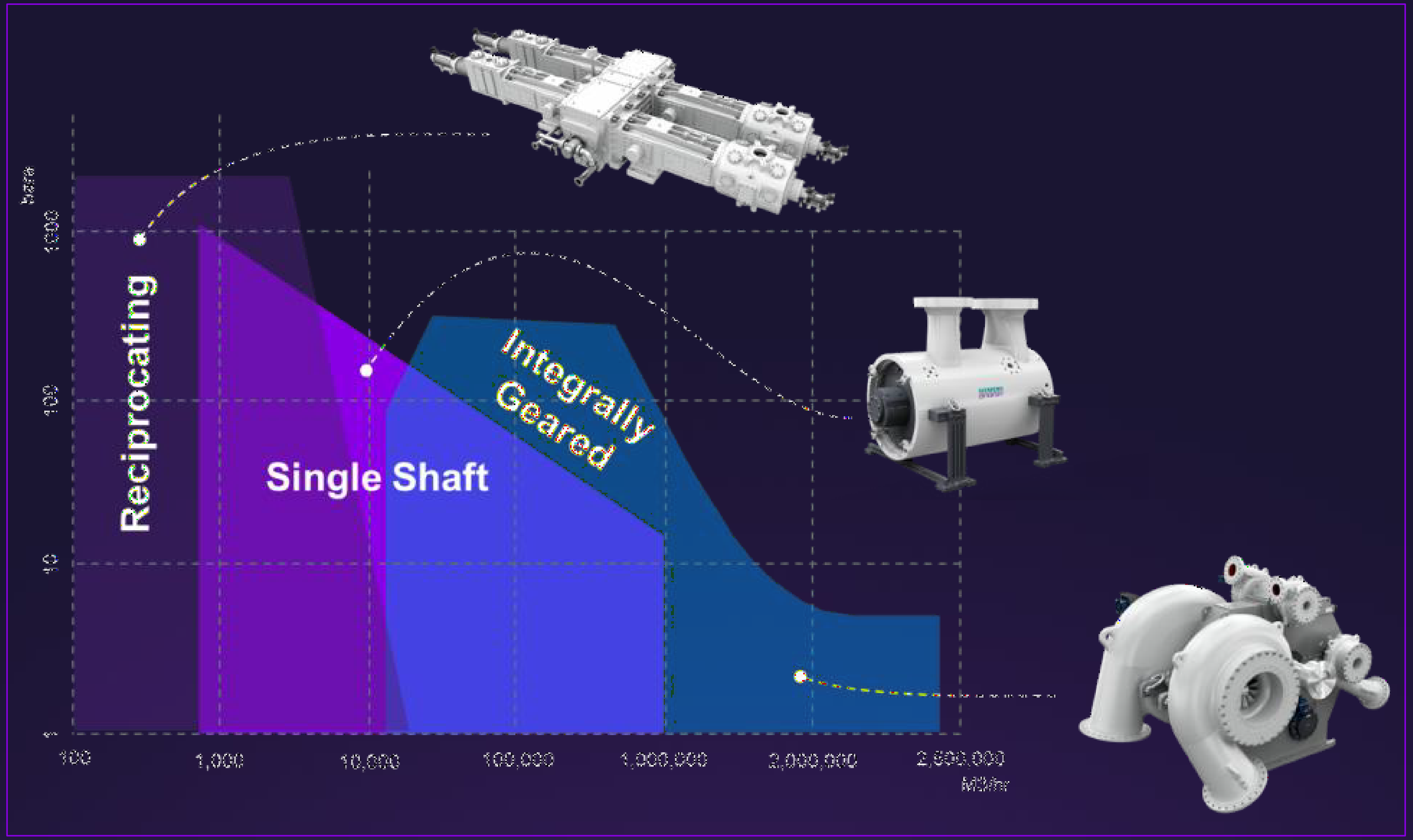


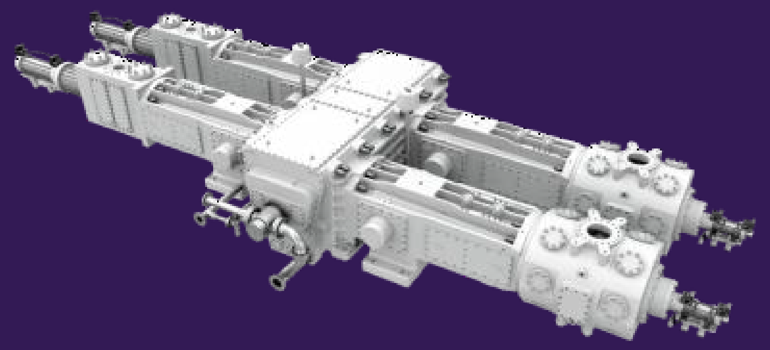
Equipment Specification

Corrosion risks increase equipment costs

Material upgrades: A stream with water and other contaminants like NOx and SOx poses the risk of forming nitric acid and sulfuric acid, potentially requiring a material upgrade from standard stainless steel to high-grade chrome alloys.

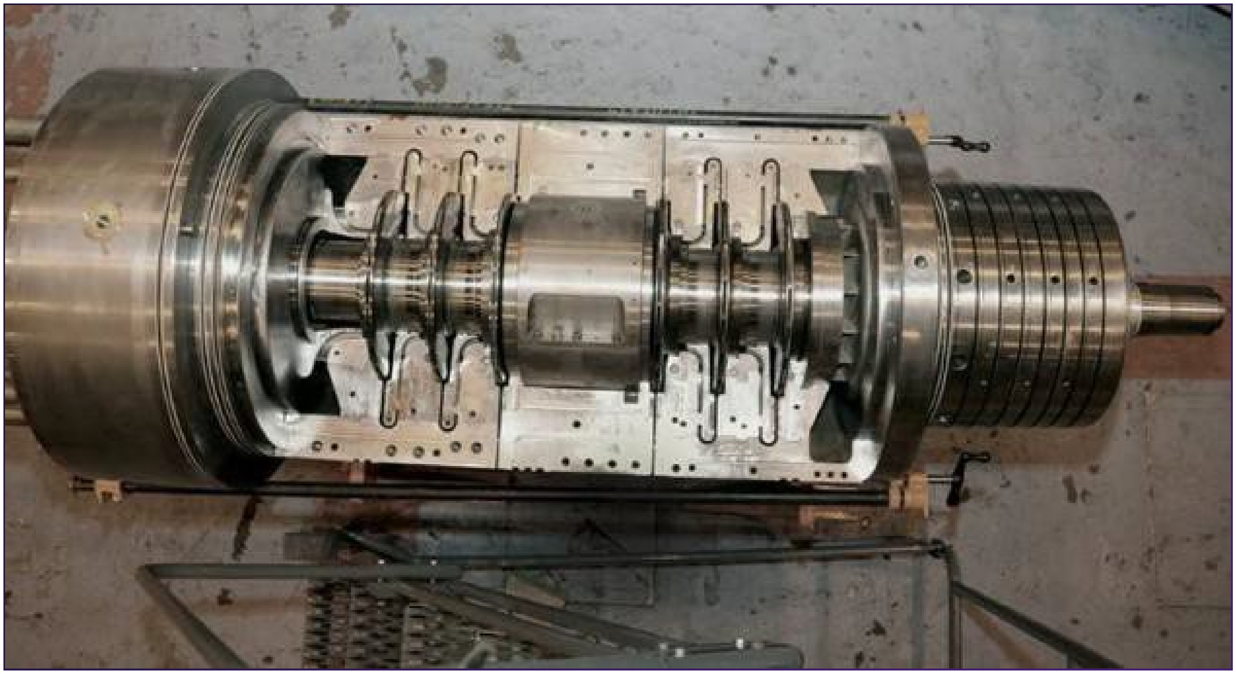
Building on Experience





Over **130** References with CO_2 primarily for injection

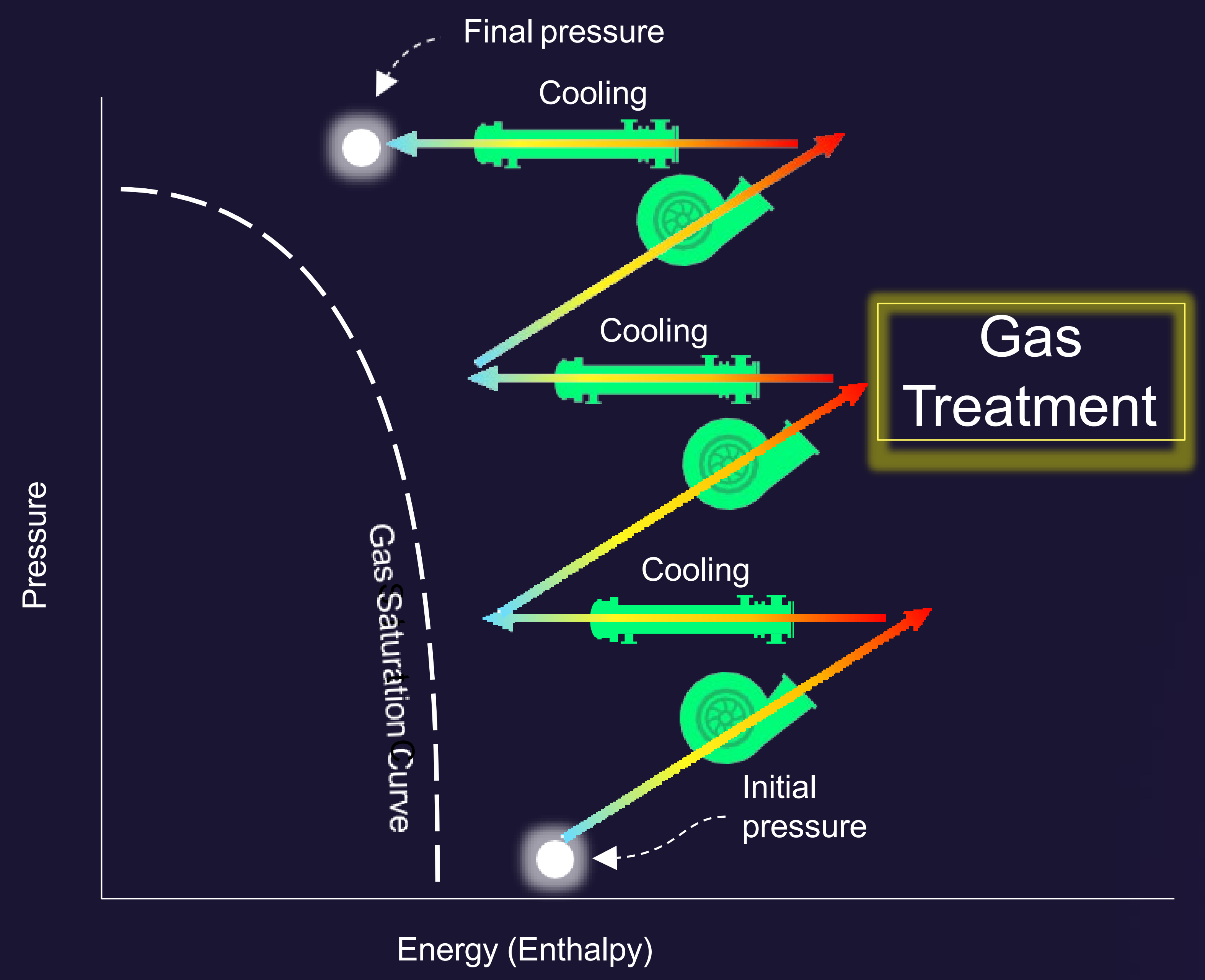
Over **60** references in CO_2 primarily for injection and urea



Over **25** references in CO_2 primarily for post-capture export

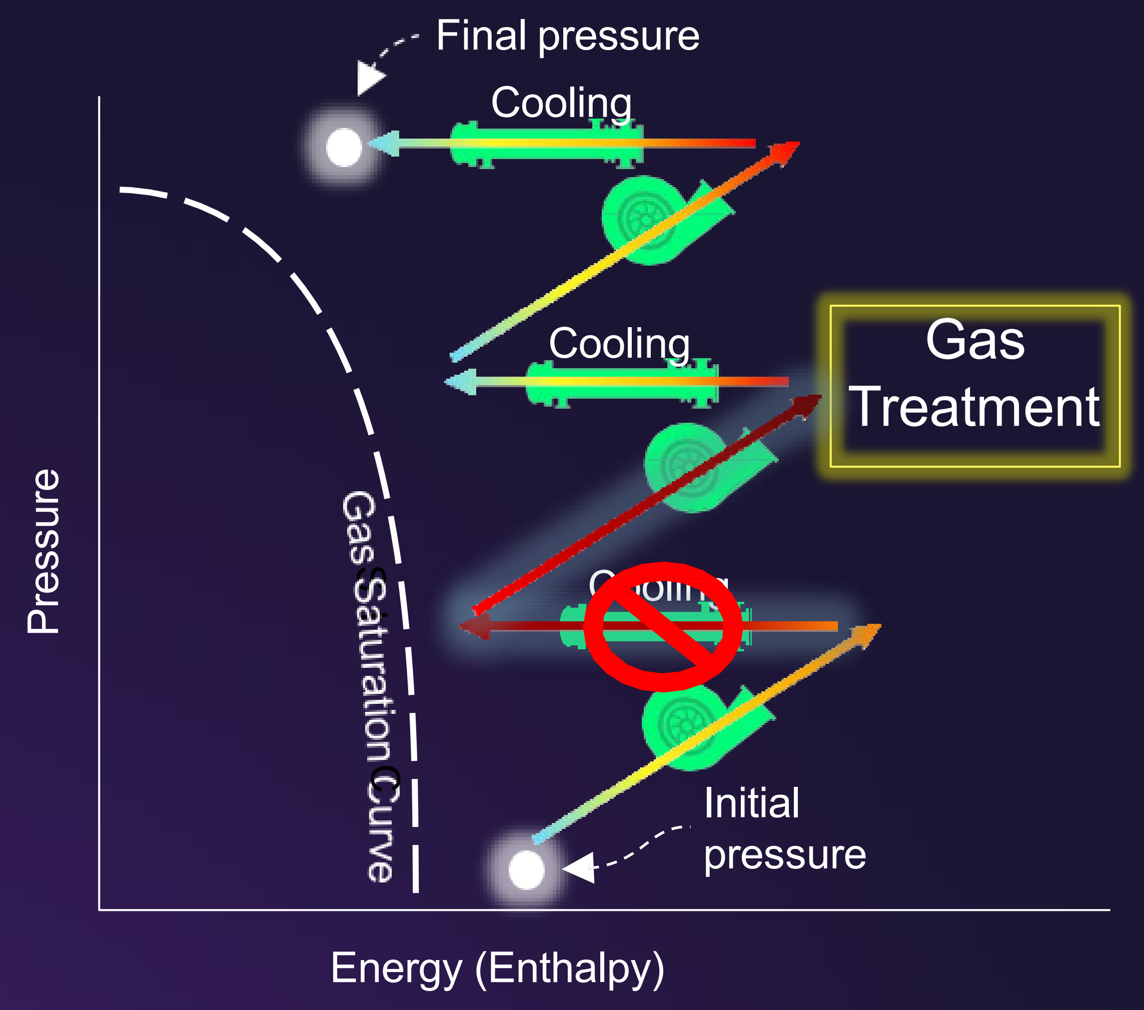
SE TI CP

Optimization Opportunities – Compression Heat



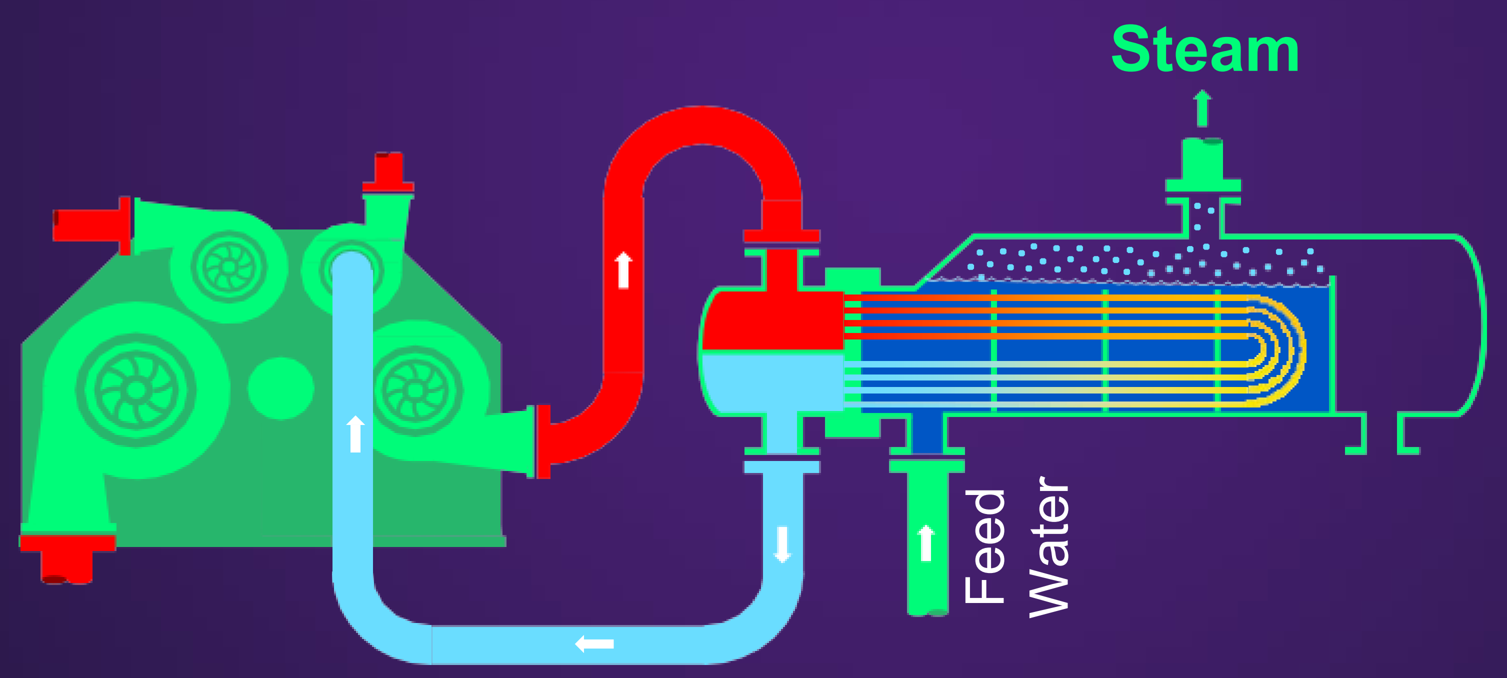
Compression Induced Superheating

- Maximize discharge temperature
- Reduces reactor heater duty
- CAPEX ⬇ OPEX ⬇



Heat Recovery

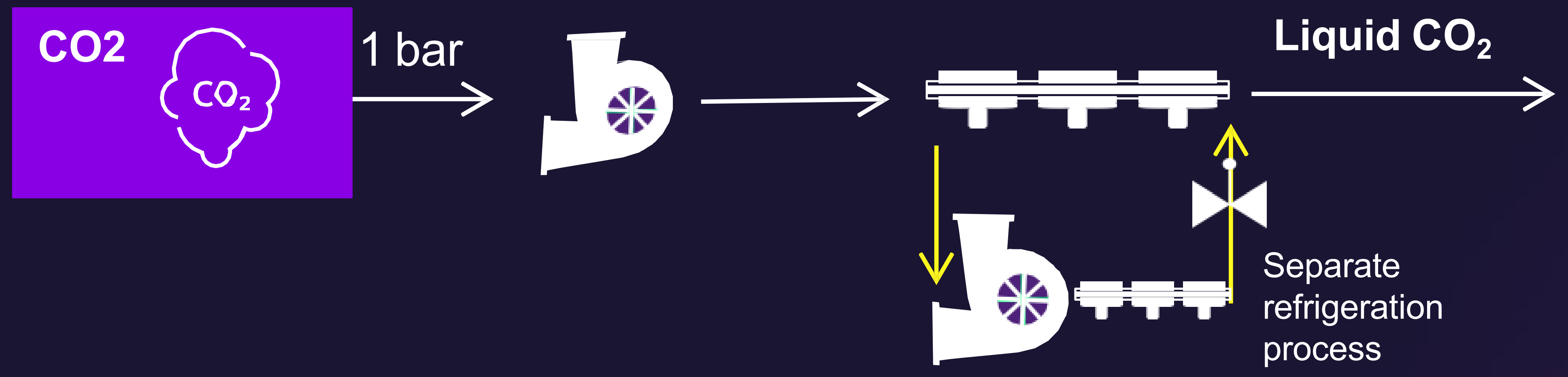
- Heat of compression is typically wasted
- Can be recovered to reduce process heat demand (amine regeneration)
- Steam demand ⬇ Associated Emissions ⬇



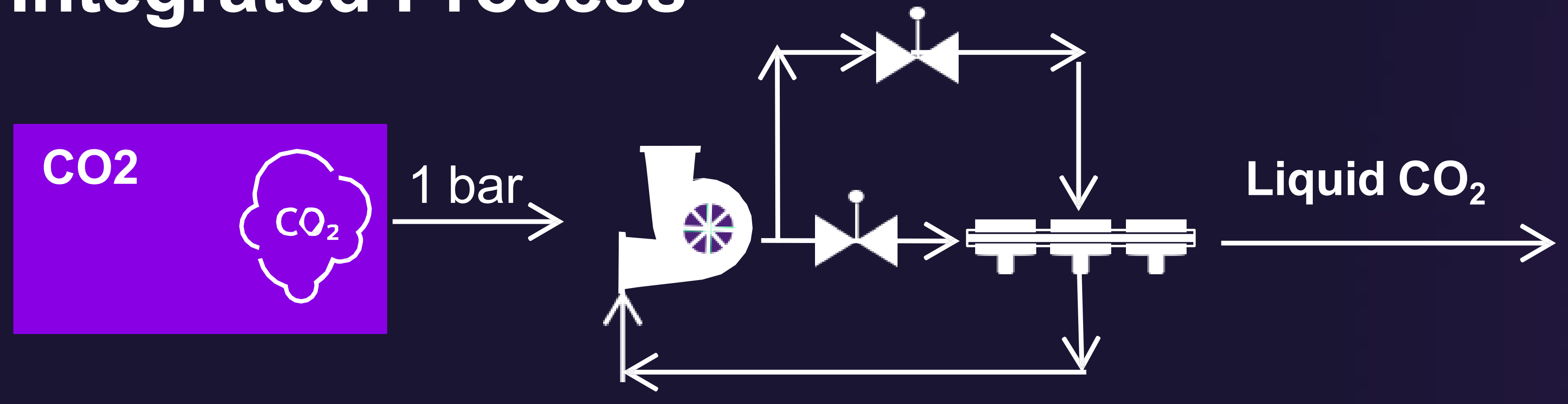
Optimization Opportunities - Process Integration

Liquefaction

Traditional Process



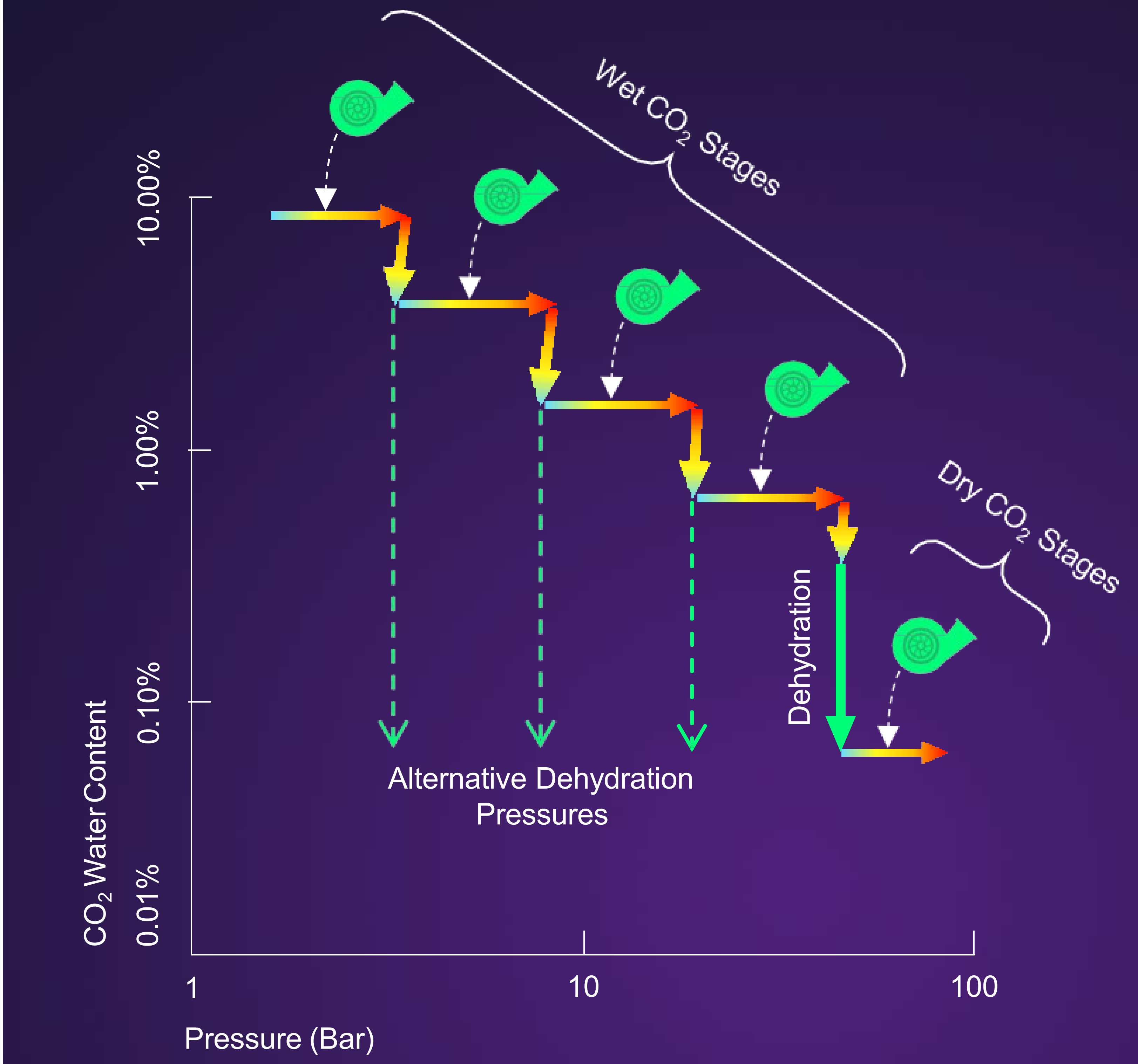
Integrated Process

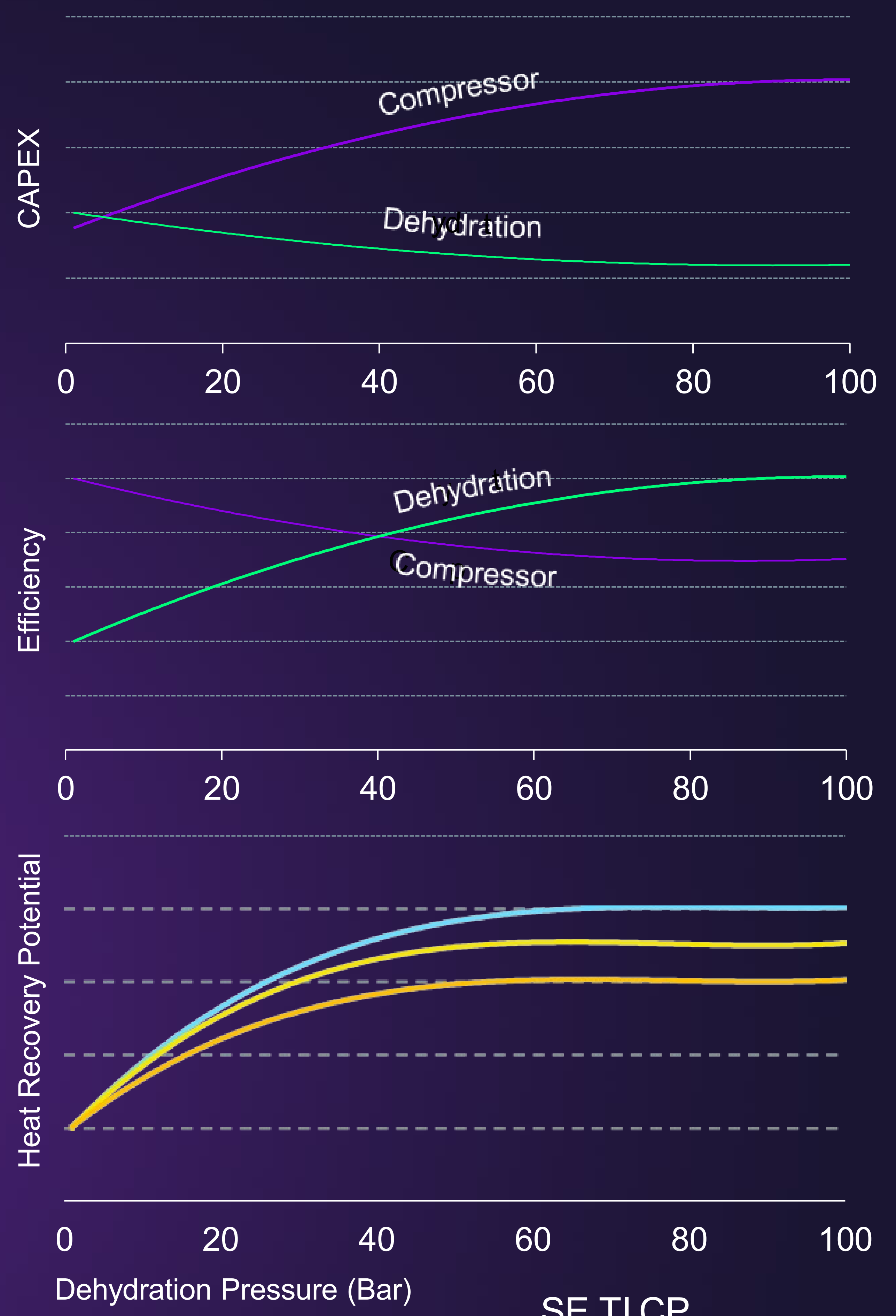


Dehydration

In various applications, the dehydration process occurs during the compression of CO2. Both systems are highly co-dependent, and should be designed simultaneously.

Project specific drives, such as CAPEX and OPEX, can be deeply optimized when both systems are designed in an integrated way.





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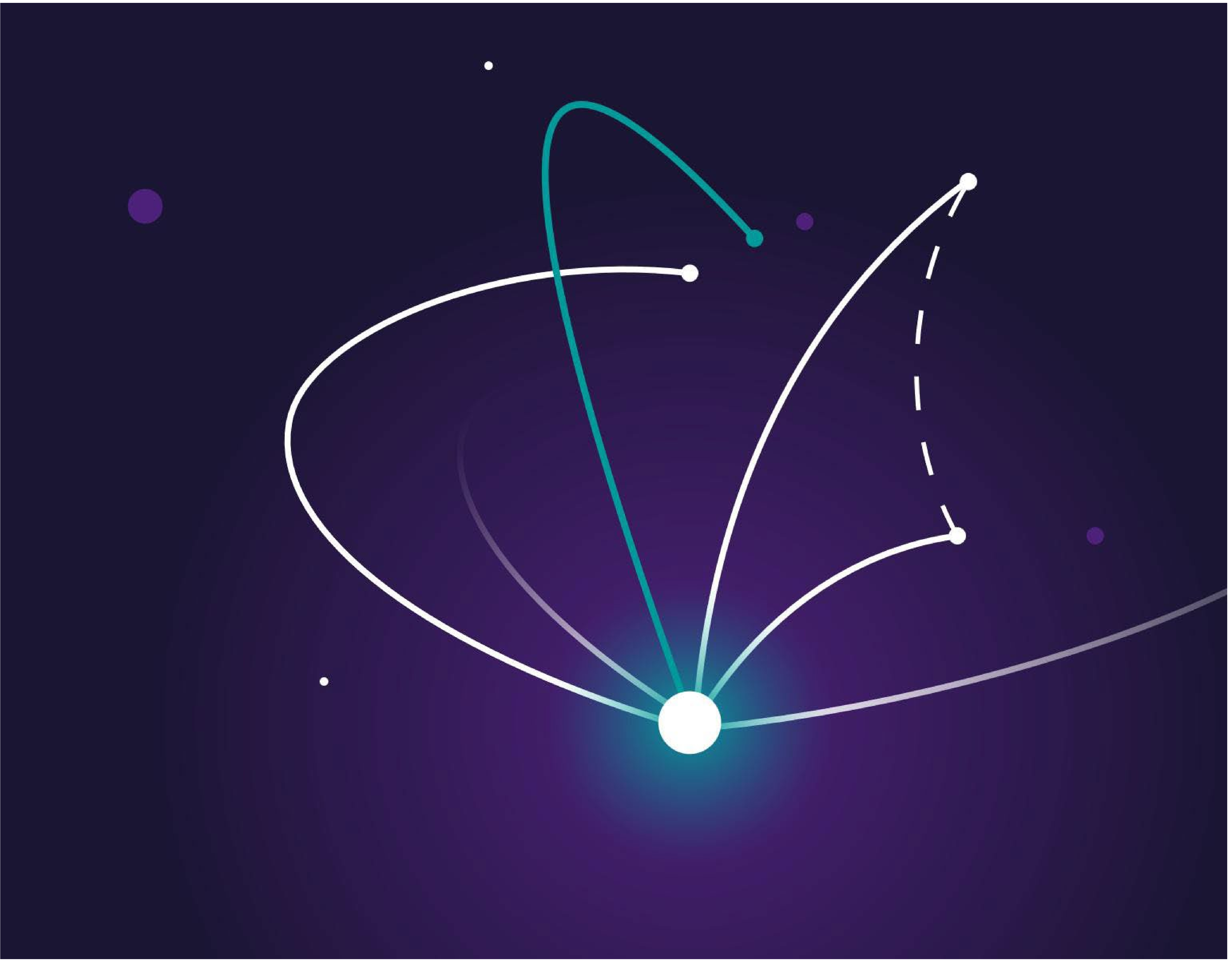

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KNOWLEDGE 20
SHARING 26
CCS & CDR Summit

#KNOWLEDGESHARING2026

Marcel de Vries

TECHNICAL LEAD CCS TECHNOLOGY EXPERTISE CENTRE

GASUNIE

As Technical Lead of the CCS Technology Expertise Centre at Gasunie, Marcel de Vries brings together deep engineering expertise and real-world delivery. With a background spanning energy, process industry and innovation, he leads international efforts on robust CO_2 specifications—turning complex science into safe, scalable CCS solutions that accelerate the energy transition.

GASSNOVA

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zep

IEAGHG

MI CARBON DIOXIDE REMOVAL MISSION

Full of new energy

Route towards safe and cost-efficient CO_2 specifications over the CCS value chain

15-04-2026

Marcel de Vries

CCS Technology Expertise Centre

Gasunie

Agenda

- Introduction
- Why are CO_2 Specifications & Impurities important?
- Ongoing research activities
- Key takeaways

Our network for tomorrow’s energy

Natural gas

Green gas

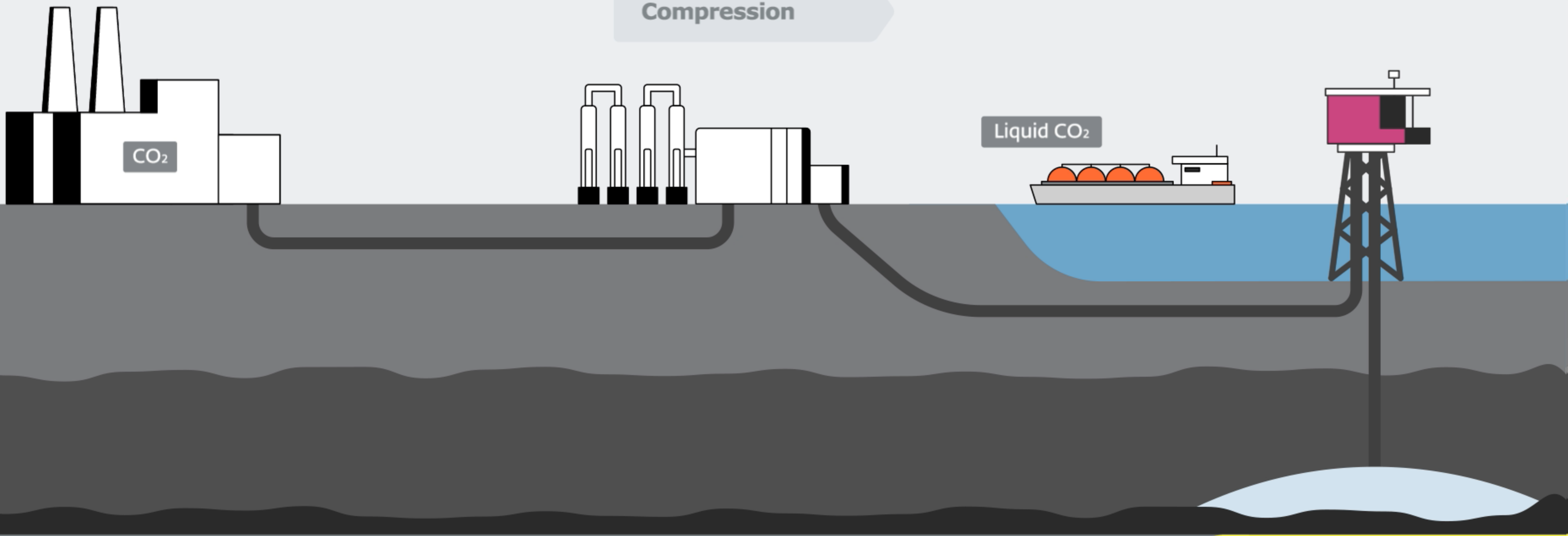
Hydrogen

CO_2

Heat

CCS Value Chain – Gasunie's role

- Emitter
- Ship
- Onshore Pipeline
- Utilization
- Terminal
- Compression
- Offshore Pipeline
- Storage



CCS Program overview

CCS Program overview

CCS Program overview

Why are CO2 Specifications & Impurities important?

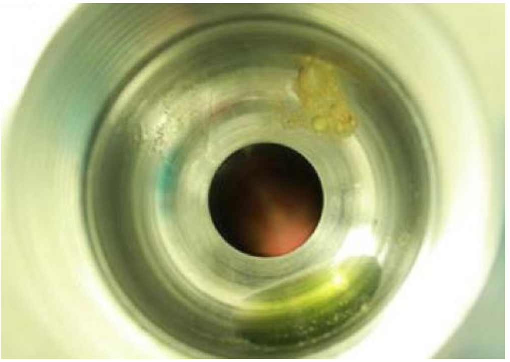
- Reactive impurities in CO_2 streams, such as H_2O, O_2, H_2S, SOx, and NOx, can form sulfuric (H_2SO_4) and nitric acids (HNO_3)

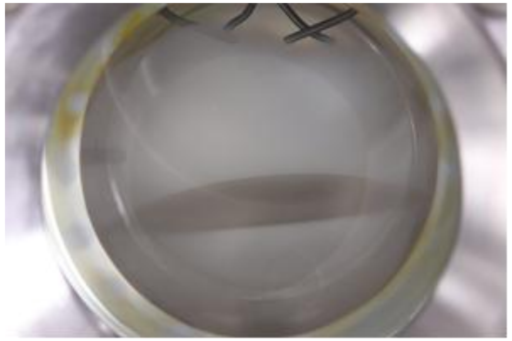
- When these acids exceed their solubility limits, they form a separate liquid acidic phase and introduce additional corrosion mechanisms and threats.

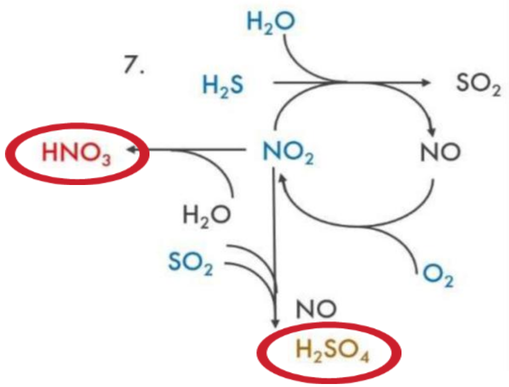
- Until 2024, both Porthos and Aramis have a published CO_2 specification which was considered to be safe
- Since then, acid dropout and surface corrosion observed at various conditions below project specifications

- Occurs in gas phase, dense phase and cryogenic liquid phase

- Network-effect

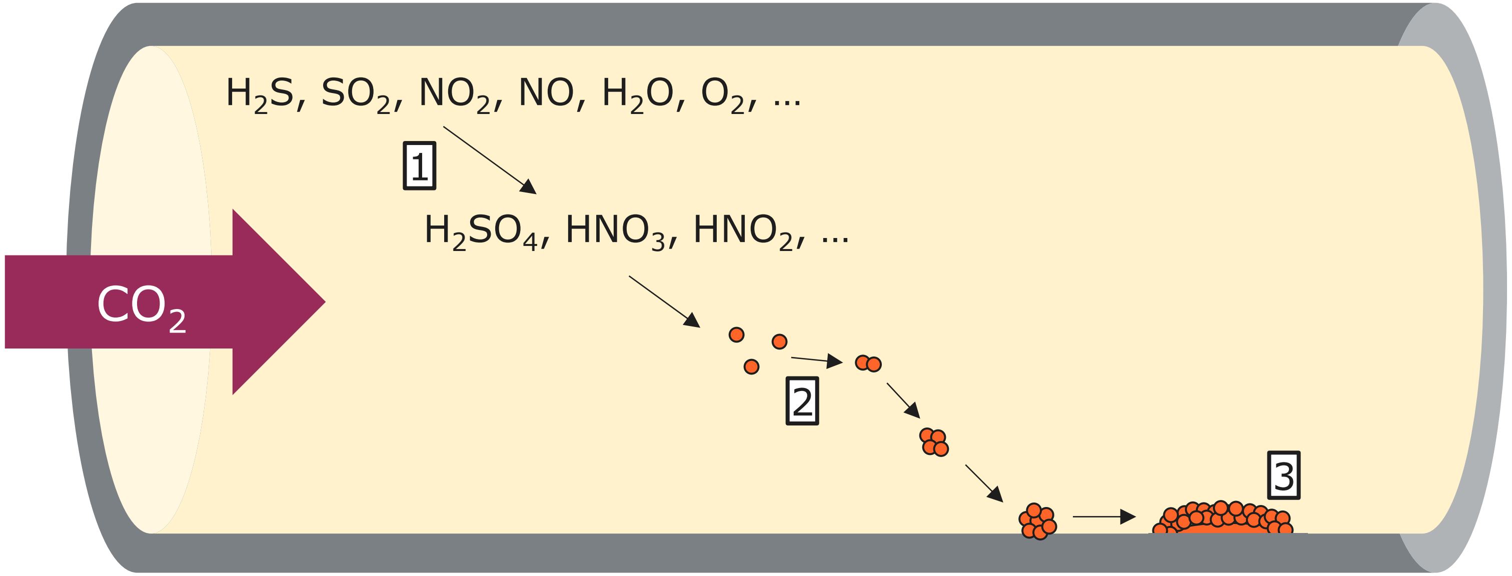






Corrosion Control Based CO2 Specification – A project approach; J. Sonke et al.; Eurocorr 2025-54592; Sep 2025
Corrosion and chemical reactions in impure CO2; J. Sonke et al.; 2024
Impurity Reactions in Gaseous and Liquid CO2 Streams; B.H. Morland et al.; AMPP C2024-20788

Steps potentially leading to acid dropout & corrosion



Expected Reactions

R1 $H_2S + 3\,NO_2 \leftrightharpoons SO_2 + H_2O + 3\,NO$

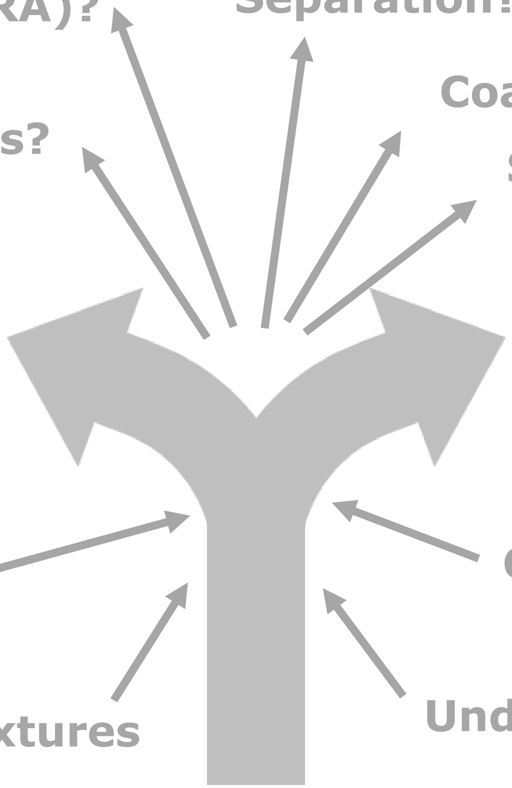
R2 $SO_2 + H_2O + NO_2 \leftrightharpoons H_2SO_4 + NO$

R3 $2\,NO_2 + H_2O(l) \leftrightharpoons HNO_3 + HNO_2$

R4 $2\,NO + O_2 \leftrightharpoons 2\,NO_2$

1. Bulk phase reactions
   - Allowable composition
   - Phase (p, T)
   - ***Kinetics***
2. Droplet formation
   - ***Solubility***
   - Nucleation
   - Growth
   - Precipitation
3. Corrosion
   - Refresh rate
   - ***Surface reactions***
   - Heterogeneous reactions

Several options and ways forward...



Corrosion Resistant Alloys (CRA)?

Upstream Separation?

Scavengers & Inhibitors?

Coatings or Cladding?

Separate CO_2 Networks?

Low or no NOx approach? (Limit oxidation)

Low or no sulphur approach? (Limit specific product)

Influence of complete CO_2 mix

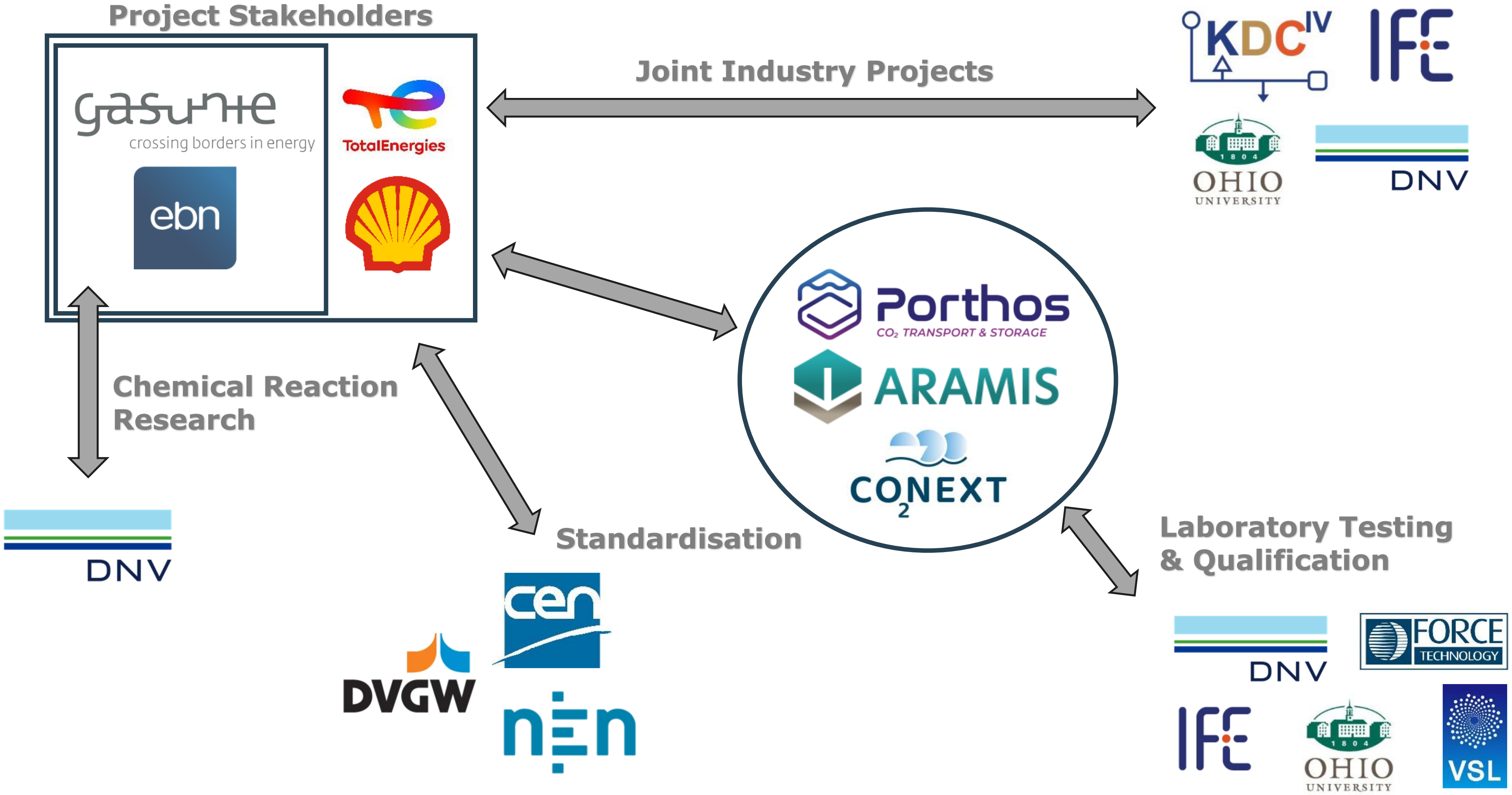
Commercially achievable lower limits

Actual achievable industrial CO_2 mixtures

Understanding of reaction kinetics

Goal: "Safe & cost-efficient CO_2 Network"

Research activities



Project Stakeholders

Joint Industry Projects

Chemical Reaction Research

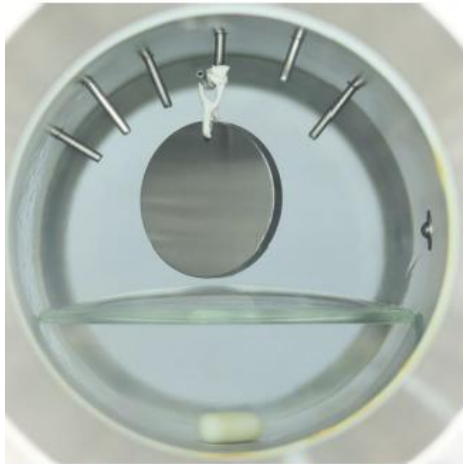
Standardisation

Laboratory Testing & Qualification

Porthos/Aramis CO_2 Impact Team

Gasunie/EBN/Shell/TTE

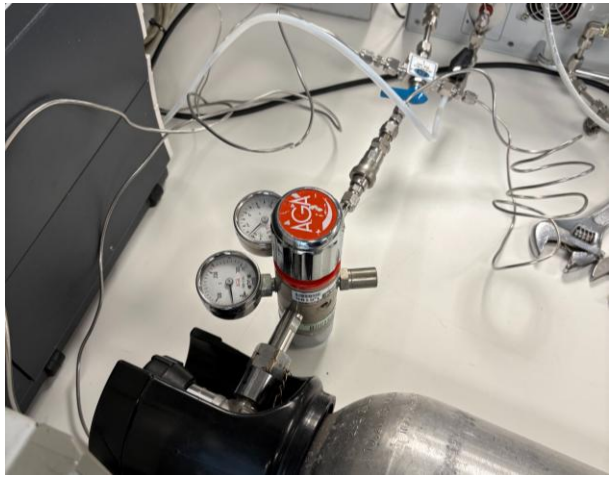
- Collaboration between experts from JV partners
- Aligning on combined test program
  - Composition testing
    - Flow through & batch reactors
    - Test range for combinations of big 5
    - Various conditions: pressure and temperature (gas, dense, cryo)
    - Determine whether other component have an effect (methanol, aldehydes, amines, etc.)
  - Corrosion
    - Coupons present in most experiments
    - Limited corrosion rate experiments
- Feedback emitters on composition direction & feasibility
- Outlook: ideally one spec for gas & dense, a separate cryogenic/shipping spec

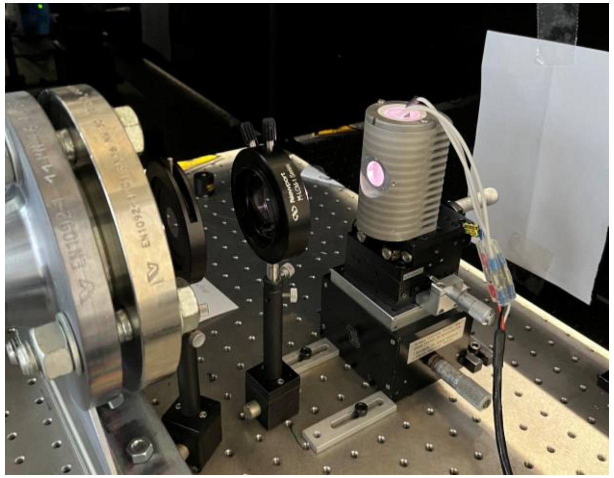


DNV Technology Centre Groningen

Gasunie/EBN

- CO_2RE: CO_2 composition & chemical reaction testing
  - Determine the kinetics of reactions in the bulk phase that could lead to acid formation
  - In-situ optical composition measurements
  - Investigate droplet formation under flow conditions (flow loop)





DNV Technology Centre Groningen

Gasunie/EBN

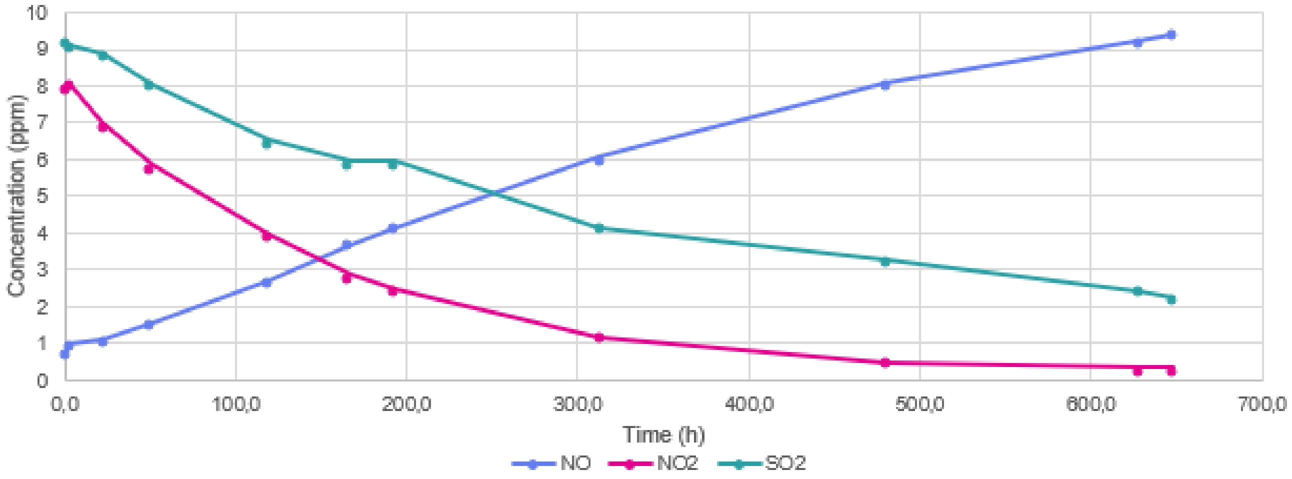
Preliminary results:

- R1 (H_2S) happens very fast (gas-phase)
- R2 (SO_2) is a slower reaction (gas-phase)
- Kinetics not conclusive yet
- In-situ measuring principle works!

Reaction of NO_2 with SO_2 and water

- $NO_2 + SO_2 + H_2O \rightarrow H_2SO_4 + NO$

- Starting with 10 ppm NO_2 and 10 ppm SO_2
- In gas phase (40 bar) and nitrogen environment



Knowledge sharing

- Periodic updates and results soon available via website! www.dnv.com/co2re/

DNV

Key takeaways

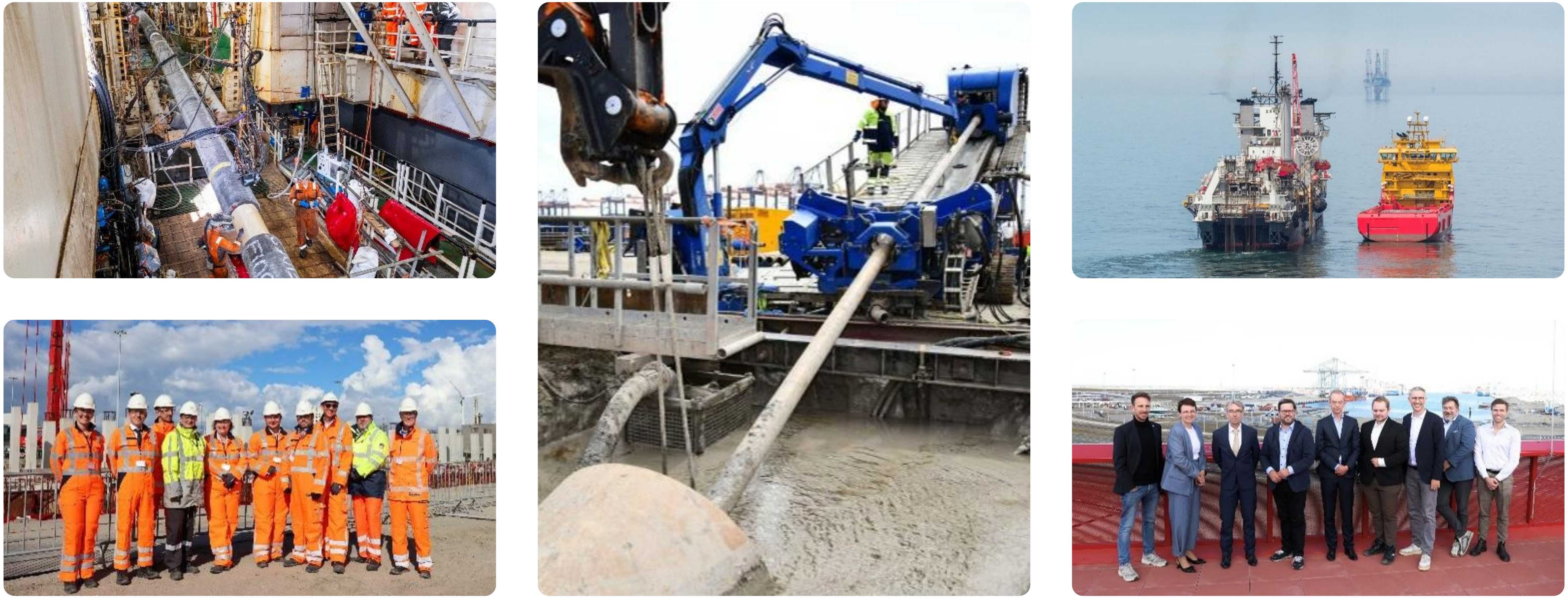
- CO_2 specification is not a competitive element, but a safety and integrity issue
- Wrongly defined specs can cause corrosion, with potential LOC risks—impacting all CCS projects globally. This could trigger regulatory changes and harm public acceptance of CCS

- Further research in e.g. reaction kinetics, droplet formation, flow dynamics and corrosion impact is needed to form a complete image of potential/actual corrosion issues and reduce conservatism (relax specifications)

- Project specs → cross-border CO2 network; ambition to have an aligned spec with CEN and neighboring networks

- Collaboration is key: CO_2 spec involves many interdependent variables. The global research capacity is limited—avoid duplication and aim to share results across CCS projects

CCS: We have started!



Thanks!

More information

Sign up for the newsletter

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Full of new energy

KNOWLEDGE 20
SHARING 26
CCS & CDR Summit

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Chris Phillips

EXECUTIVE CONSULTANT

WOOD

Chris Phillips is an Executive Consultant at Wood, providing advisory services on developing safe and cost effective CCS value chains. He recently managed the IEAGHG report reviewing strategies and costs on CO_2 Conditioning Technologies and led the Joint Industry Project that produced Industry Guidelines for Setting the CO_2 Specification in CCUS Chains.

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IEAGHG

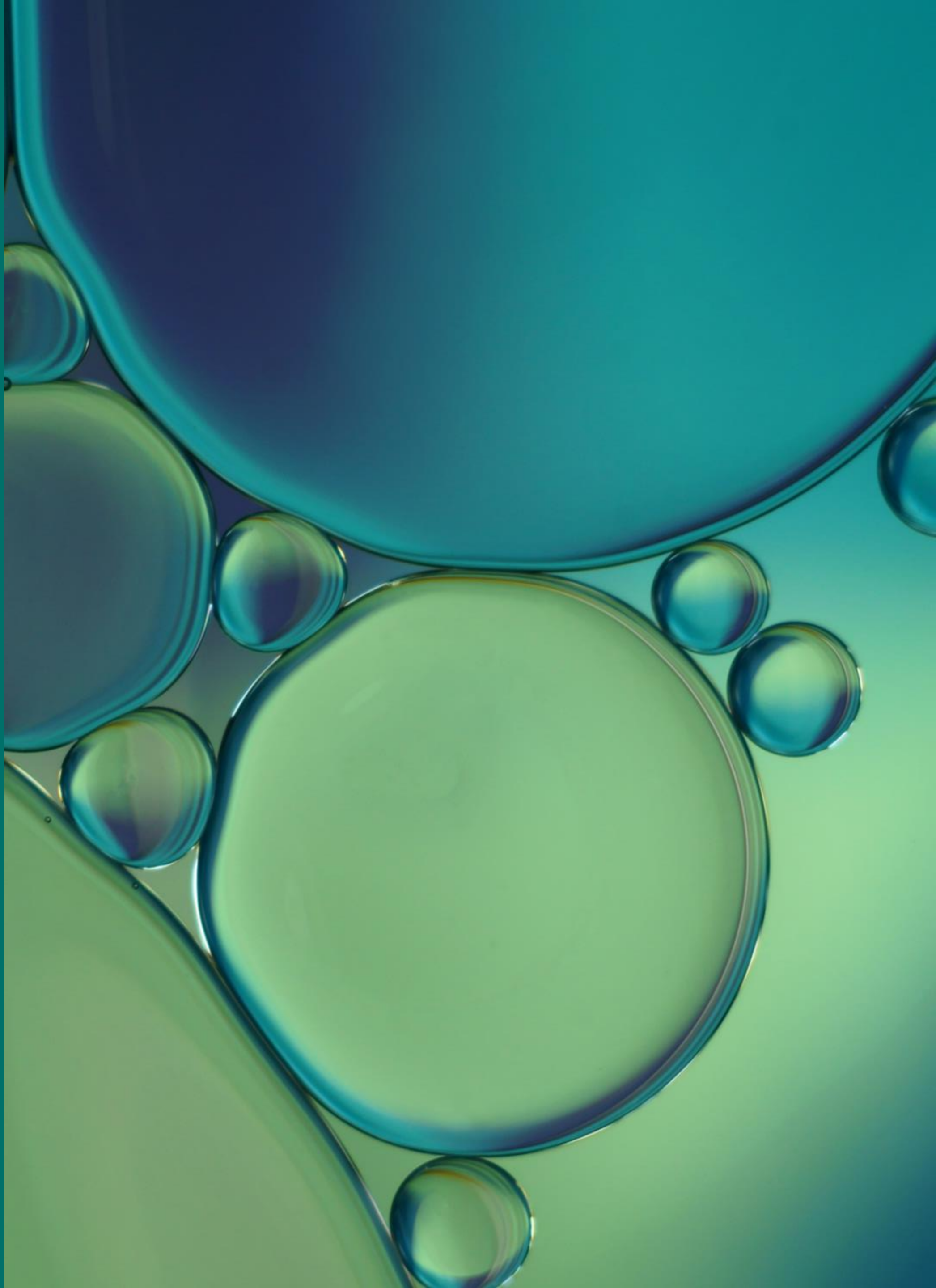
CARBON DIOXIDE REMOVAL
MISSION

CO_2 Conditioning Technologies -

IEAGHG - Strategies and Cost Considerations for Commercial Deployment

Chris Phillips, Wood

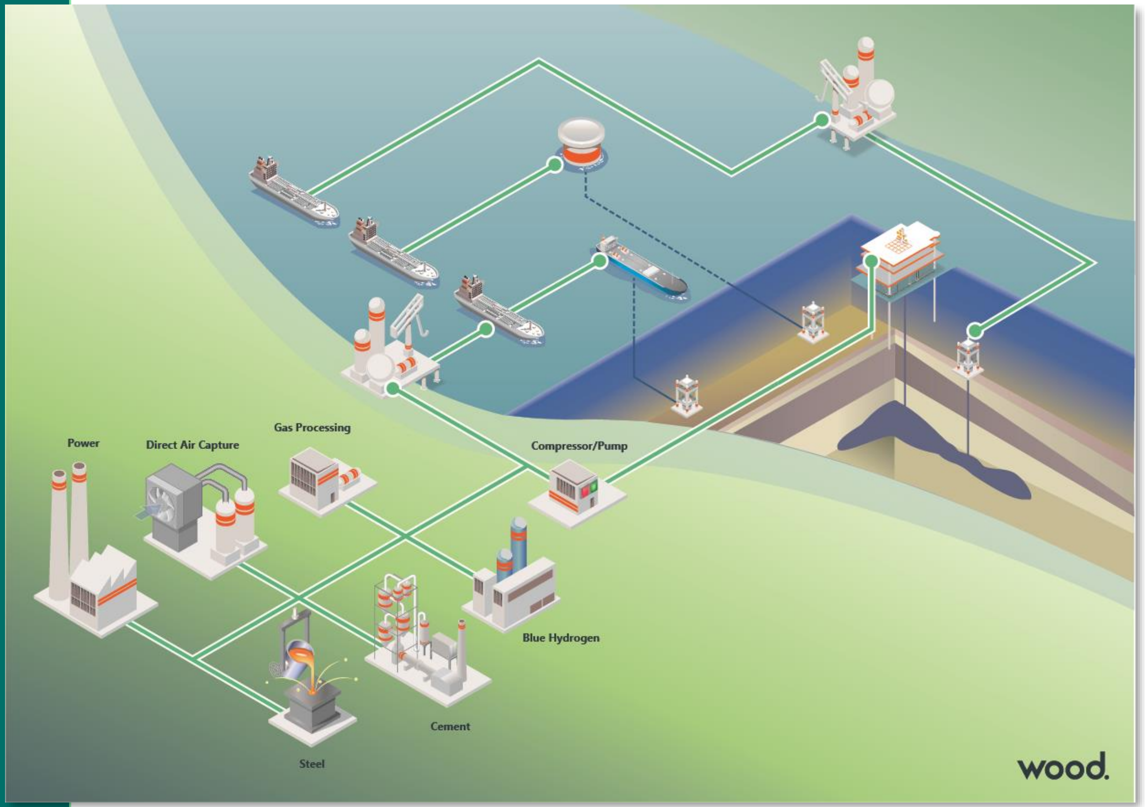
April 2026



IEAGHG Study Aims

Conduct a robust assessment of CO_2 conditioning technologies:

- Assess the impact of impurities on the CCS chain
- Conduct an economic assessment for implementing CO_2 conditioning technologies
- Investigate how CO_2 specifications influence material selection.
- Develop strategies for the commercial deployment of CO_2 conditioning technologies.



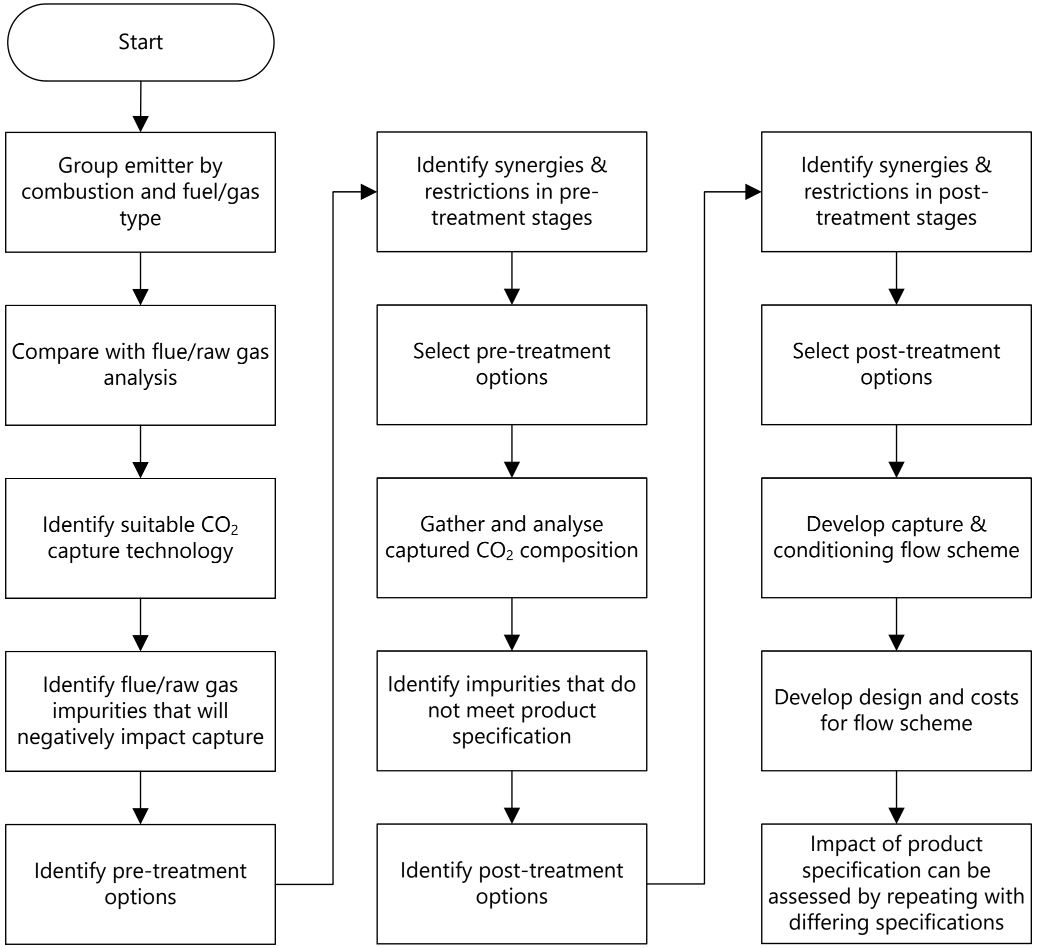
Report Contents

Task	Summary
Task 1 – CO_2 Conditioning – Context and Overview	Overview of CO_2 conditioning landscape and the sources of impurities.
Task 2 – Advanced Metrology for CO_2 Purity	Review of CO_2 sampling / analysis technologies and challenges and monitoring recommendations.
Task 3 – CO_2 Specification	Literature review of standards projects and basis for setting CO_2 specifications.
Task 4 – Impurities Impact Assessment	Impurities from fuel type, industries and capture / conditioning processes. Assesses impurity impacts across the CCUS chain and discusses strategies to reduce impurities.
Task 5 – Review of Conditioning Technologies	Comprehensive review of impurity removal processes and industry examples.
Task 6 – Influence of CO_2 Specifications on Materials	Impacts of impurities on materials and latest research on acid / solid formation.
Task 7 – Economic Analysis of CO_2 Conditioning	Levelised costs for main conditioning technologies with industry examples.
Task 8 – Centralised vs Local CO_2 Conditioning	Strategies for deployment and where scale can pay off.
Task 9 – Overall Conclusions and Summary	Concludes how impurities drive safety, integrity, cost, and specification choices.

Task 3 - Creating Economic CO_2 Specifications

- Removing impurities (e.g. fuel switching)
- Minimising impurities (e.g. low NO_X burners, coal cleaning)
- Reviewing the CO_2 Capture Technology (e.g. solvent carryover)
- Minimise number of purification steps (e.g. Removing multiple impurities in a single process)
- Review total impurities not just individual limits (e.g. consider interactions between SO_X, NO_X, H_2S, O_2, and H_2O)
- Transportation Pathway (ship / truck / train vs pipeline)

Capture & Conditioning development methodology [1]



Start

Group emitter by combustion and fuel/gas type

Compare with flue/raw gas analysis

Identify suitable CO_2 capture technology

Identify flue/raw gas impurities that will negatively impact capture

Identify pre-treatment options

Identify synergies & restrictions in pre-treatment stages

Select pre-treatment options

Gather and analyse captured CO_2 composition

Identify impurities that do not meet product specification

Identify post-treatment options

Identify synergies & restrictions in post-treatment stages

Select post-treatment options

Develop capture & conditioning flow scheme

Develop design and costs for flow scheme

Impact of product specification can be assessed by repeating with differing specifications

---

1. CO_2 specification JIP https://www.woodplc.com/insights/reports/Industry-Guidelines-for-Setting-the-CO2-Specification-in-CCUS-Chains

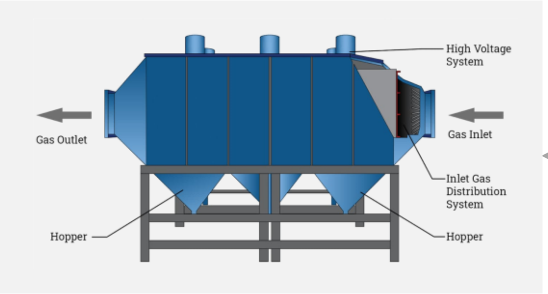
Task 4 - Impacts of Impurities (non-exhaustive)

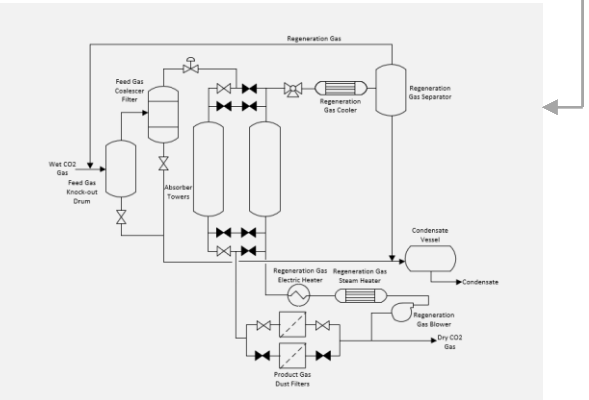
Component	Comment
Water	Water reacts with carbon dioxide to produce corrosive carbonic acid. Water can also react with NO_X, SO_X, O_2 and H_2S to form strong corrosive acids. There is also a risk of hydrate formation.
H_2S	Highly toxic. May react with other compounds to form acids and elemental sulphur. The acids have a high potential for corrosion and the elemental sulphur may lead to clogging. H_2S may lead to sulphide stress corrosion cracking with water.
SO_X / NO_X	Can react with water to form a highly corrosive aqueous acid phase.
CO	Toxic gas. Risk for CO-CO_2 cracking if a free water phase is formed.
O_2	Oxygen is a cause of corrosion in wet conditions. Oxygen enhances the formation of elemental sulphur and sulphuric / nitric acid if SO_X / NO_X are present. May cause biological growth in reservoirs and injectivity issues.
N_2 / Ar / CH_4 / H_2	Non-condensable 'light' substances: Ar, CH_4, H_2, C_2H_6 (also H_2S, O_2, CO). Can increase the two-phase region in phase envelope - reduces density and viscosity. Reduces the molecular weight and increases compression duty. In liquids increases the vapour pressure which may require higher pressure to supress vaporisation.
H_2	H_2 can lower the tensile strength of steels and accelerate fatigue crack growth at relatively low hydrogen partial pressures.
Amine	Amines may react with and degrade several non-metallic materials.
Alcohols / Aldehydes	Increases the fluid dew point causing the stream to condense at higher temperatures. Potential operability issues.

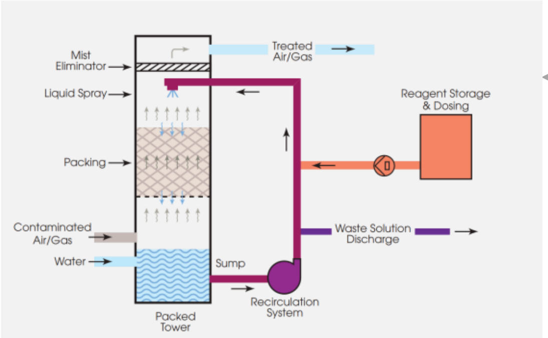
Task 4 - Impurities from Industry

Source	Fuel / Gas Type	Mol% CO_2	Major Impurities
Coal-fired power plant	Coal & Oil	12 to 15	N_2, water, O_2, NO_X, SO_X, particulates, NH_3
Gas power plant	Clean Gas	4 to 5	N_2, water, O_2, NO_X, SO_X
Steel	Coal & Oil	5 to 20	N_2, Ar, CO, SO_X, H_2S, COS, HCN, HCl, H_2, heavy metals
Cement	Biomass & Waste	15 to 30	N_2, water, O_2, NO_X, SO_X, CO, NH_3, particulates, heavy metals, VOCs, acids
Waste incineration	Biomass & Waste	5 to 15	N_2, water, O_2, HCl, H_2S, NO_X, SO_X, CO, NH_3, particulates, heavy metals
Biomass boiler	Biomass & Waste	5 to 15	N_2, water, O_2, SO_X, NO_X, HCl, HF, particulates
Anaerobic Digestion Plant	Biogas	40 to 60	N_2, water, O_2, CO, H_2, siloxanes, NH_3, alcohols
Direct Air Capture	Air	4×10^{-4}	N_2, O_2, Ar, water
Hydrogen (Steam Methane Reformer)	Fuel Gas / Tail Gas	15 to 25	H_2, N_2, CH_4, CO, water
Sour Natural Gas	Acid gas	1 to 30	CH_4, H_2S, COS, CS_2, hydrocarbons including BTEX

Task 5 – Review of CO_2 Conditioning Technologies





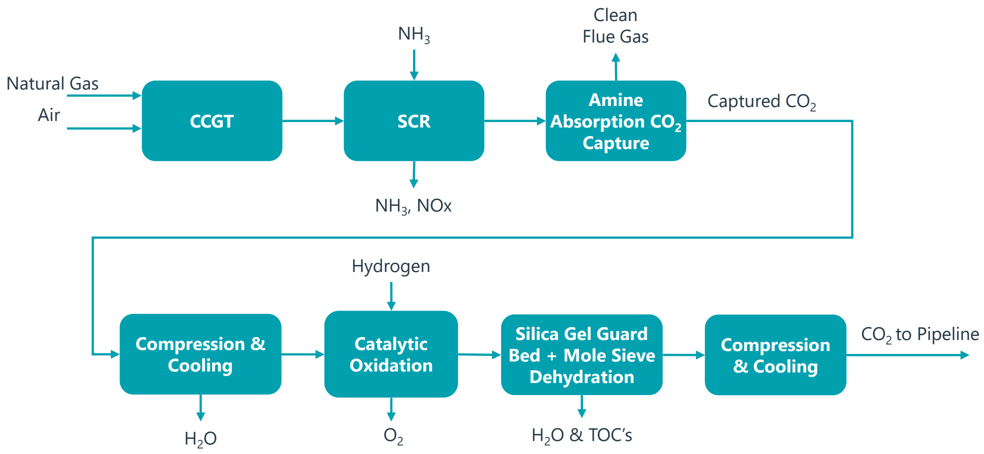


Impurity Removal Technology	Impurities Removed
Fabric Filter	Particulates + caustic dosing: Acids (HCl, HF)
Candle Filter	Particulates
Electrostatic Precipitation	Particulates + Wet ESP: SO_3, Sulphuric Acid Aerosols
Compression & Cooling	H_2O
Liquid Desiccants	H_2O
Molecular Sieve	H_2O, Mercury & Heavy Metals, Hydrocarbons, VOCs, BTEX
Silica Gel	H_2O
Activated Alumina	H_2O
Catalytic Oxidation	O_2, H_2, CO, CH_4, HCN
Catalytic Hydrolysis	HCN, COS, CS_2
Solid Scavenger Adsorption	O_2
Cryogenic Distillation	O_2, H_2, CO, Non-Condensables
Selective Catalytic Reduction	NO_x (HCN, CO, VOCs to varying efficiencies)
Selective Non-Catalytic Reduction	NO_x
Caustic Direct Contact Cooler	NO_x, SO_x, H_2S, COS, Acids (HCl, HF), HCN
Flue Gas Desulphurisation	SO_x
Catalytic Oxidation & Adsorption	H_2S, CS_2, COS, CH_3SH, Mercaptans, VOCs, BTEX, HCN, SO_2
Activated Carbon	SO_x, Mercury and Heavy Metals, Hydrocarbons, VOCs, BTEX, HCN
Water Wash	Amines, Ammonia, Aldehydes, Acids (HCl, HF), HCN, Alcohols
Acid Wash	Amines, Ammonia, Aldehydes
Separation Membranes	H_2, CO, Non-condensables
Mixed Metal Sulphides	Mercury & Heavy Metals
Scavengers	H_2S, HCl, HF (+ hydrogenation: sulphur, halides, and mercaptans)
Redox/Thiopaq™ / Claus	H_2S
Thermal Oxidation	Hydrocarbons, VOCs, BTEX, CO

Task 5 - Industry Examples

Power Generation (Gas Turbine)

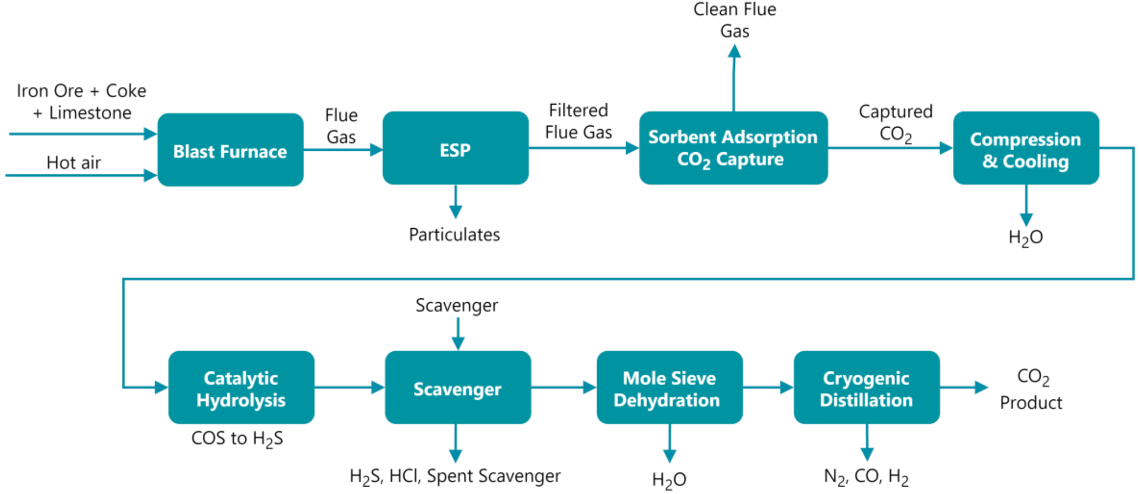
(for pipeline transport)



Natural Gas
Air
CCGT
NH_3
SCR
NH_3, NOx
Clean Flue Gas
Amine Absorption CO_2 Capture
Captured CO_2
Compression & Cooling
H_2O
Hydrogen
Catalytic Oxidation
O_2
Silica Gel Guard Bed + Mole Sieve Dehydration
H_2O & TOC's
Compression & Cooling
CO_2 to Pipeline

Steel Industry (Blast Furnace)

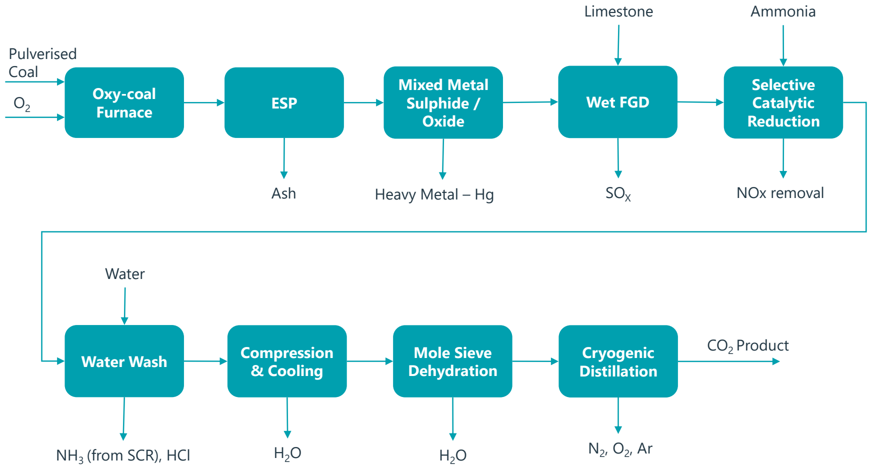
(for pipeline / shipping transport)



Iron Ore + Coke + Limestone
Hot air
Blast Furnace
Flue Gas
ESP
Particulates
Filtered Flue Gas
Sorbent Adsorption CO_2 Capture
Clean Flue Gas
Captured CO_2
Compression & Cooling
H_2O
Catalytic Hydrolysis
COS to H_2S
Scavenger
Scavenger
H_2S, HCl, Spent Scavenger
Mole Sieve Dehydration
H_2O
Cryogenic Distillation
N_2, CO, H_2
CO_2 Product

Power Generation (Oxy-Coal Combustion)

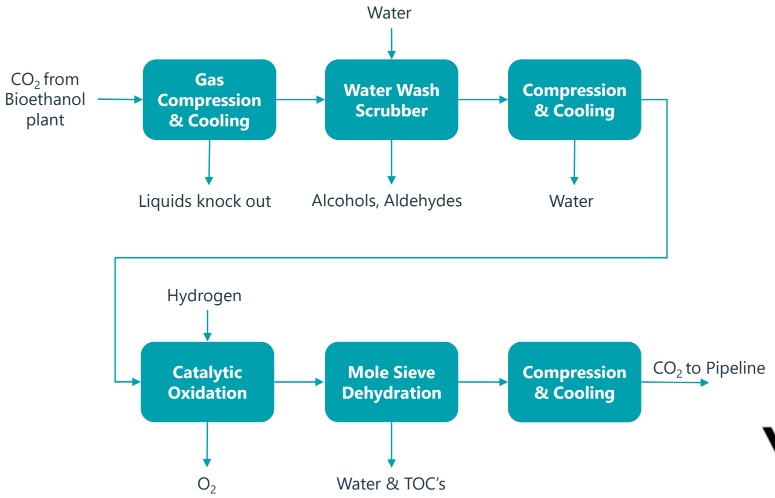
(for pipeline / shipping transport)



Pulverised Coal
O_2
Oxy-coal Furnace
ESP
Ash
Mixed Metal Sulphide / Oxide
Heavy Metal – Hg
Limestone
Wet FGD
SO_x
Ammonia
Selective Catalytic Reduction
NOx removal
Water
Water Wash
NH_3 (from SCR), HCl
Compression & Cooling
H_2O
Mole Sieve Dehydration
H_2O
Cryogenic Distillation
N_2, O_2, Ar
CO_2 Product

Bioethanol Production

(for pipeline transport)



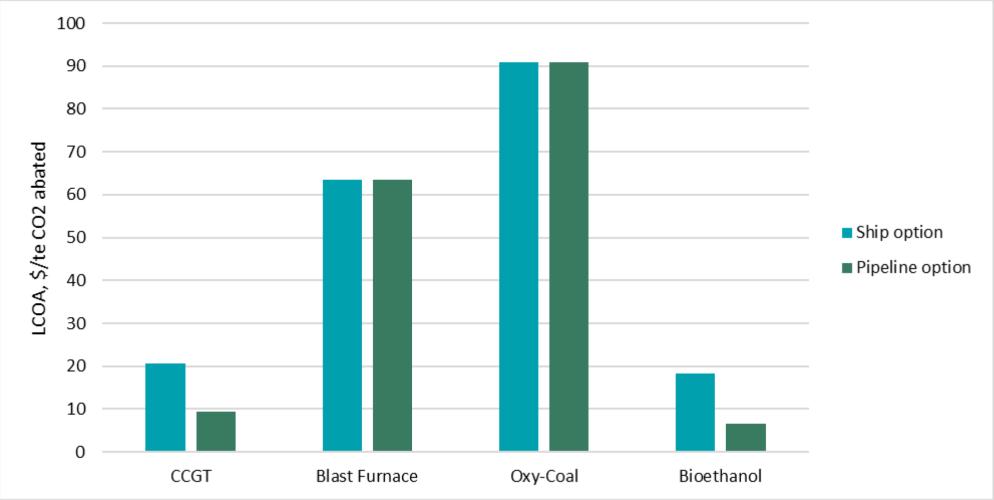
CO_2 from Bioethanol plant
Gas Compression & Cooling
Liquids knock out
Water
Water Wash Scrubber
Alcohols, Aldehydes
Compression & Cooling
Water
Hydrogen
Catalytic Oxidation
O_2
Mole Sieve Dehydration
Water & TOC's
Compression & Cooling
CO_2 to Pipeline

Task 7 – Cost of Conditioning Technologies

- Introduced a method for calculating the Levelised Cost of CO_2 Abatement (LCOA).
- Determined the cost of CO_2 conditioning for each of the selected industries to meet either a pipeline or shipping CO_2 Specification.
- Lowest LCOA is for Bioethanol, due to high purity of CO_2 produced and low conditioning requirements.
- Highest LCOA is for Oxy-Coal power plant.
  - Bulk inert gas removal with consequential higher power consumption at the cryogenic distillation unit.
  - High assumed SO_X and NO_X impurities require FGD and SCR installation ~50% of total cost.

Levelised Cost of Abatement

$$\boldsymbol{LCOA}\ (\$/\boldsymbol{MWh}) = \frac{\sum_{t=1}^{t=n} \frac{\boldsymbol{Annual\ investment\ cost\ in\ year\ t}}{(1+r)^t}}{\sum_{t=1}^{t=n} \frac{1}{(1+r)^t}}$$



FGD – Flue Gas Desulphurisation for removing SO_X
SCR – Selective Catalytic Reduction for removing NO_X
CCGT – Combined –Cycle Gas Turbine

Task 6 - Influence of CO_2 Specification on Materials

- Reviewed the impact of CO_2 stream specifications on the materials required for CCUS

- Summary of the existing materials guidance on:
  - material selection for CCUS chains including cost implications
  - how impurities affect material integrity (corrosion / cracking)
  - corrosion control and management

- Latest research and new learnings for material selection.

Suggested Base Case Materials Selection[1]

Component	CO_2 phase	Selected material	LDT
Pipework	Gas phase	LT-CS	-40°C
Compressor + coolers	Dense phase	ASS 316	-80°C
Pipework onshore	Dense / Liquid	ASS 316	-80°C
Storage tanks (including ship cargo tanks)	Liquid	3.5 Ni-steel	-80°C
Pipeline	Dense phase	LT-CS + 3 mm C.A. (C.A. can be project specific)	-40°C
Pipework offshore / Coastal	Dense phase	SASS 6 Mo ASS 316 + TSA	-80°C
Wells **Wellhead / Tree** **Casing / Hanger**	Dense phase	Alloy 625 L 80 CS low alloy steel, typical F22 or AISI 4130	-80°C -40°C
Seal materials	Dense phase	For direct contact, carbon or metallic seals are preferred.	

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1. AMPP Guide 21532-2023, "Guideline for Materials Selection and Corrosion Control for CO_2 Transport and Injection," 2023.

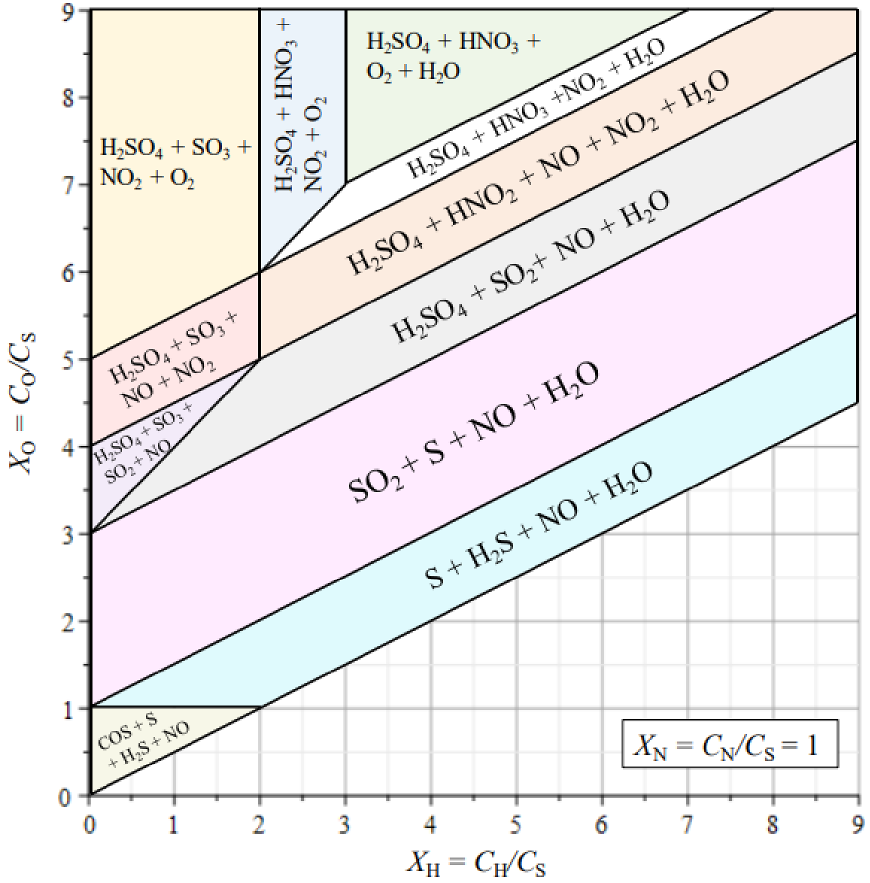
Task 6 - Acid / Solids Formation through Reactions

Latest research on acid / solids formation

- Creation of sulphuric acid, nitric acid and elemental sulphur.
- At 100 bar acid-forming reactions can occur at room temperature.
- There is also evidence of acid formation at low temperatures associated with ship transport.
- Acid formation requires the presence of water (to form H^+) as well as an oxidizing environment.
- In an environment with a reducing tendency, water or elemental sulphur can be formed.

Acid formation reactions
$H_2O + SO_2 \rightarrow H_2SO_3$
$H_2O + SO_2 + ½\, O_2 \rightarrow H_2SO_4$
$H_2S + 3NO_2 \rightarrow SO_2 + H_2O + 3NO$
$2\ NO + O_2 \rightarrow 2NO_2$
$H_2O + NO_2 + SO_2 \rightarrow NO + H_2SO_4$
$H_2O + 3NO_2 \rightarrow 2HNO_3 + NO$
$H_2O + 2\ NO_2 \rightarrow HNO_2 + HNO_3$
$3\ HNO_2 \rightarrow HNO_3 + 2NO + H_2O$
$2\ H_2S + 3O_2 \rightarrow 2SO_2 + 2H_2O$
Sulfur reactions
$8\ H_2S + O_2 \rightarrow S_8 + 8H_2O$
$H_2S + 2NO_2 \rightarrow 2NO + H_2O + ½SO_2 + ½\ S$
$2\ H_2S + SO_2 \rightarrow 3S + 2H_2O$
$H_2S + HNO_3 \rightarrow 3S + 2NO + 4H_2O$
$H_2S + H_2SO_4 \rightarrow S + SO_2 + 2H_2O$
Acid-base reactions (solids)
$CO_2\ (g) + 2NH_3\ (g) \rightarrow NH_4CO_2NH_2\ (s)$
Amines+CO_2 → ammonium salts +++

Stability Diagram for N:S=1, Slavchov et al[1]



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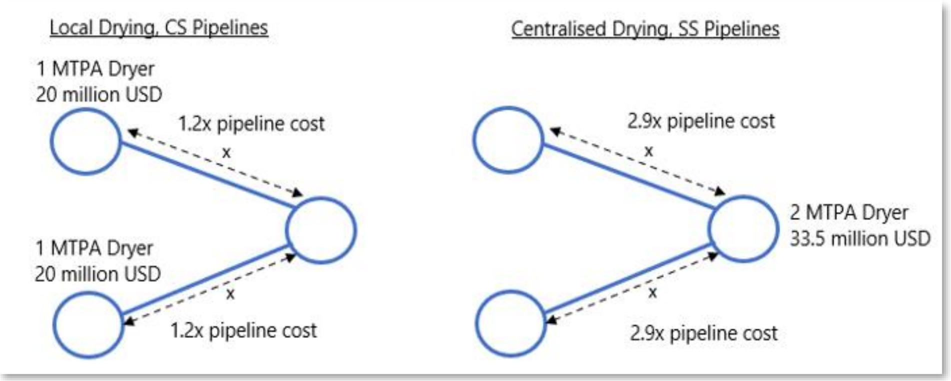
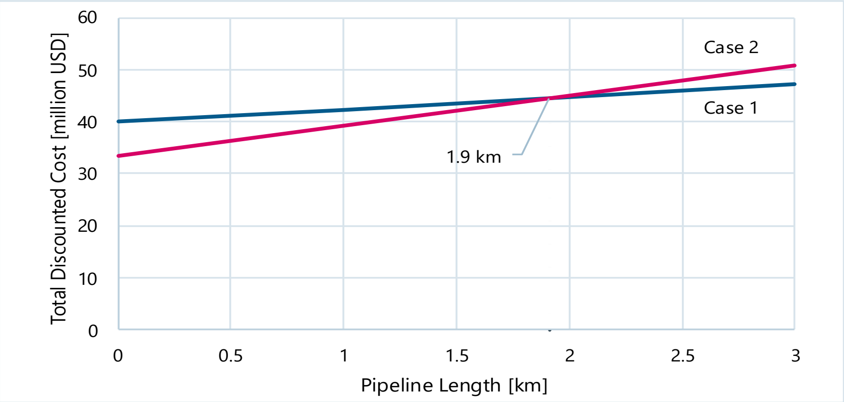
[1] R. I. Slavchov, H. Batool, S. Faraji, D. Madden, J. Sonke, S. Clarke, Corrosion maps: Stability and Composition Diagrams for Corrosion Problems in CO_2 Transport, Corrosion Science 236, (2024) 1122024. https://www.sciencedirect.com/science/article/pii/S0010938X24003998

Task 8 - Centralised vs Local CO_2 Conditioning

- Investigated centralised conditioning of combined CO_2 streams versus local conditioning by each emitter.
- To maximise economies of scale centralised conditioning is generally only considered for high purity streams (i.e. post-capture or from industries that do not require capture).
- In a referenced example[1], centralised dehydration was not economic when the centralisation facilities were more than 2 km from the source industries.
- Centralised distillation could still be desirable for inerts removal.

Centralised vs Local Conditioning [1]





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1. CO_2 specification JIP https://www.woodplc.com/insights/reports/Industry-Guidelines-for-Setting-the-CO2-Specification-in-CCUS-Chains

Task 2 - Advanced Metrology for CO_2 Purity

- Current CCS monitoring technologies and engineering standards reviewed, with key limitations identified.
- Major challenges identified: supercritical CO_2 properties, gaps in fluid property models, lack of calibration facilities, and evolving legislation.
- Online and offline sampling methods from oil & gas generally applicable, but no proven method for representative liquid or supercritical CO_2 sampling; analysis requires vaporisation.
- Online and offline monitoring options reviewed for impurities identified in ISO 27913. Online monitoring is recommended for each of the key impurities as well as trace components that are liable to absorb to or react with internal surfaces of the sampling system.
- Key sampling and analysis challenges: traceable reference materials, analysers which are accurate under stream conditions, proven sample system materials, proven methods for representative sampling, and validated analytical methods.

Task 9 - Overall Conclusions

- CCUS chains should be set up with transparency between stakeholders to understand the CO_2 specification and target the minimum costs for conditioning.

- Removing / minimising impurities at source is a key strategy for minimising conditioning costs

- Consider economic strategies when selecting conditioning technologies include waste treatment and by-product management as part of the assessment.

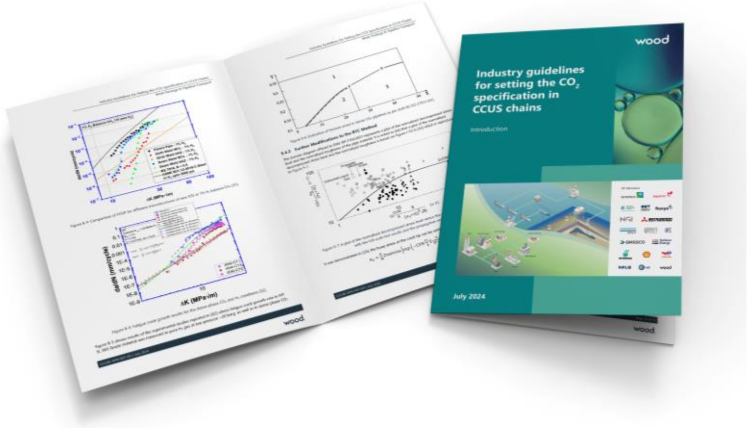
- Continuous CO_2 monitoring for critical impurities (H_2O, O_2, NO_X, SO_X, H_2S, H_2, methanol).

- Sampling and analysis challenges: traceable reference materials, accurate online analysers, proven sampling systems and methods.

- Further research is required to assess multi-component impurity behaviour.

CO_2 Specification JIP

- The study draws on findings from the CO_2 Specification JIP which can be downloaded for free



wood

Industry guidelines for setting the CO_2 specification in CCUS chains

Introduction

July 2024

Link to the Guidelines

Free – open access

https://www.woodgroup.com/insights/reports/Industry-Guidelines-for-Setting-the-CO2-Specification-in-CCUS-Chains

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equinor
fluxys
GASSCO
Harbour Energy
MITSUBISHI HEAVY INDUSTRIES
Net Zero Technology Centre
Technology Driving Transition
OMV
PETRONAS
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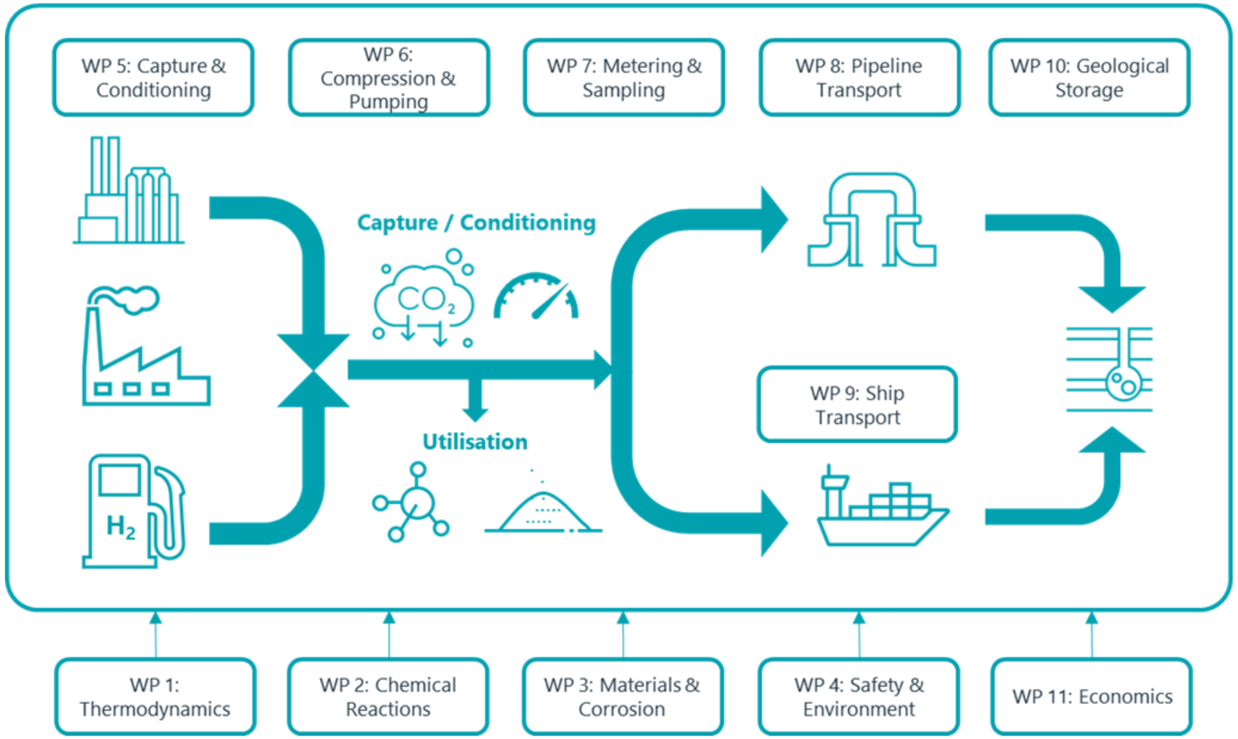

WP 5: Capture & Conditioning
WP 6: Compression & Pumping
WP 7: Metering & Sampling
WP 8: Pipeline Transport
WP 10: Geological Storage
WP 9: Ship Transport
WP 1: Thermodynamics
WP 2: Chemical Reactions
WP 3: Materials & Corrosion
WP 4: Safety & Environment
WP 11: Economics

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